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Timber Façade Structures: Using Thermal Analysis to Prognosticate the Ignition Resistance of Flame-Retarded Timber

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Abstract: The development of a methodological approach to detecting the presence of flame retardants in building materials and products and finding their concentration is an essential part of the performance evaluation of flame retardants for timber. The above issue is a relevant constituent of supervision over fire safety compliance at construction facilities. Thermal analysis was used in this research project to (1) detect the presence of flame retardants in timber, and (2) identify methods of their application. Comparative experiments were conducted to detect the presence and effectiveness of flame retardants applied to the surface and inner layers of specimens of timber planken (façade board) at a construction facility. Relevant values, characterizing the thermal decomposition of timber specimens, enable predicting the heat flux rate that triggers ignition. A quick test, conducted to check the flammability of specimens, confirmed the authors' hypothesis. The study revealed principal (relevant) thermo-analytical criteria for the fire resistance of timber impregnated with combustion retardants using different methods of impregnation. A methodological approach to studying relevant thermo-analytical characteristics was developed to evaluate the efficiency of (1) fire resistance of timber products and (2) fireproofing techniques. Flammability and combustibility of timber impregnated with fire retardants was prognosticated. It was revealed that the proposed methodology can monitor the efficiency of fireproofing applied to façade structures made of pine timber.

Keywords: timber fireproofing; pressure impregnation; flame retardant treatment; suspended façade system and cladding; relevant thermo-analytical characteristics; timber flammability

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1. Introduction

Multistorey timber construction is intensively developing worldwide [1,2]. Building legislation systems are amended to facilitate the construction of medium-rise and multistorey buildings that have some timber materials. The cost of construction of a timber building can be 30–40% lower than that of a traditional building made of traditional materials. Besides, the term of construction can be reduced by concentrating construction work in a particular locality [3]. Some experts argue that timber buildings are most popular in hard-to-reach areas, where heavy and oversized structures can hardly be delivered [4]. Thanks to such strengths as fast construction, environmental friendliness, energy efficiency, and climate resilience, timber structures have a great advantage over traditional structures made of brick and concrete. The term of effective operation of timber structures is also sufficiently long [5]. Properly built and operated timber buildings can be constructed in any climate zone.

However, some consumers question the quality characteristics and fire safety of timber building structures. Therefore, fire safety and introduction of advanced timber production technologies capture the attention of researchers [6,7].

Flame retardants for timber reduce fire hazards. They are widely used to protect timber building structures and products [8]. To study the effectiveness of flame retardants for timber means to study and analyze the development of combustion-retardant systems,

the mechanism of their action, methods of their application [9,10], the effect, and the quality control of flame retardants [11,12]. In [13], an attempt is made to predict the results of tests of flame-retarded timber structures. These tests were based on microscale studies of flame-retarded timber and compatibility diagrams (physicochemical characteristics and qualitative elemental analysis). In [14], the author prognosticates the fire hazard properties of construction materials. In their work, researchers Ornaghi et al., Vitázek et al., Kiefl et al., and Sharma et al. used thermal analysis to study processes of thermal degradation of timber [15–18]. However, the presence, the effectiveness of flame retardants in timber products, as well as methods of their application are not addressed in this work. The main regulatory requirements for the safe use of timber building structures and materials are provided in [19–21]. They focus on the fireproofing of rafters and purlins of attic floors, load-bearing structures of roofs (trusses, beams, etc.), façade systems of exterior walls of buildings, and structures during construction, repair, and reconstruction.

Fire safety requirements, applied to timber buildings and structures in the process of design and construction both in Russia and abroad, depend on the arrangement of buildings and structures, building-design solutions, fire resistance, and purposes. In particular, according to the Russian regulations [22,23], the number of floors in log buildings with bearing walls, made of cylindrical logs and solid timber, must not exceed two and the height must not exceed five meters. As for buildings made of glued timber, the number of floors shall not be more than three and the height shall not exceed eight meters. The height of panel and frame-panel buildings must not exceed twenty-eight meters. Buildings with more than three storeys or those that are more than nine meters high must have automatic fire-extinguishing sprinkler systems with the intensity of, at least, 0.08 L/(s m^2).

Norwegian timber buildings must not have more than four storeys, if the fire endurance of their structures is, at least, 60 min, according to [24]. Buildings with more than four storeys need additional research, namely, calculations and tests. Denmark and Iceland share timber building standards. Residential buildings can have up to four storeys, provided that they have automatic fire-extinguishing systems. If they have none, the number of storeys must not exceed two. Load-bearing structures, and exterior and interior finishing, can be made of timber in two-storey buildings. In New Zealand, the number of storeys in a building depends on the availability of fire-extinguishing systems and the fire endurance of building structures. If the height of a building is less than 25 m and this building has a fire-extinguishing system, its fire endurance can be reduced from 45 to 30 min. If the building height is more than 25 m, fire sprinkler systems are mandatory. Canada authorizes the construction of six-storey residential and public buildings made of timber [25]. Structural and combined fireproofing of building structures, as well as fire-extinguishing systems, are required.

Switzerland allows for the construction of multi-storey residential buildings whose maximum height is six storeys [26]. In Sweden, if applicable fire resistance requirements are met, no restrictions are imposed on timber as a material for load-bearing structures, but the use of unprotected timber in interior and exterior decoration is allowed in houses not higher than two floors.

A cladding system, made of timber or timber-based materials and forming the exterior layer of building elements (walls, columns, floors, plinths) and surfaces of buildings and structures, must not only ensure fire safety, but also protect the main enclosing, load-bearing structures and thermal insulation materials from atmospheric and other effects. Therefore, timber needs fireproofing, moisture-proofing, and biohazard protection [27].

Reference [28] formulates basic requirements for cladding, which serves as a protective and decorative screen for buildings, inhibits the combustion of suspended façade systems (SFSs), and protects the inner space of an SFS system from any effects from the outside. Therefore, any timber used as SFS cladding must have low water absorption, and resistance to timber-dyeing and mold fungi. Besides, this timber must belong to the group of limited-combustibility materials (combustibility group G1 [29] or fire hazard class B [30]) which preserve their fireproofing characteristics over time. The pressure impregnation

of timber with special multi-component substances ensures both quality-related and fire resistance characteristics. Authors of several works [31–33] highly appreciate both the performance and fire hazard parameters of effective pressure impregnation substances for timber. The analysis of these studies shows that the pressure impregnation of timber makes it a flame-retardant material.

Despite the studies of the effect of flame retardants on timber performance [34,35], issues related to the research-based substantiation of methods, used to detect the presence and evaluate the effectiveness of flame retardants, are sufficiently explored [36].

Combustion of cellulosic materials features remarkable heterogeneity and splits into the two main steps: combustion of gases during the thermal decomposition of the material (the flame combustion phase) and combustion of charcoal (the smoldering phase) [36]. The mechanism underlying the fireproofing of timber using flame retardants consists in modifying the process of thermal degradation to boost the emission of coke, to cut the emission of combustible gases, and to inhibit the combustion of condensed and gaseous phases. Timber fireproofing prevents ignition, decelerates the development of the initial stage of fire, reduces the fire hazard, and contributes to rapid fire suppression. The fireproofing of timber structures ensures the compliance of construction materials and structures with fire safety regulations applying to structural design.

An important task, dealing with the analysis of timber fireproofing, is to develop an approach to detecting the presence of flame retardants in building materials and products [37] within the framework of fire safety inspections. In many cases, it is necessary to evaluate the fireproofing technique, used to protect timber products, namely, to evaluate the effectiveness of surface treatment or pressure impregnation. Therefore, the development of methodological approaches to checking the effectiveness of timber fireproofing and predicting its flammability is a relevant research task to be solved in the context of the existing scope of problems.

The purpose of this project is to develop a comprehensive methodological approach to detecting the presence and evaluating the effectiveness of timber fireproofing and methods of its application, as well as to predict the ignition resistance of specimens in order to determine their further applicability, in particular, as façade cladding.

This novel methodological approach can be used to detect the presence of a fire retardant in the material, to check its effectiveness and methods of its application. Towards this end, a small amount of material is to be extracted from a facility and analyzed in the course of compliance checks.

The authors consider a specific case that consists in the feasibility of assessing the usability of flame-retarded pine board (planken) of a façade system to reconstruct a three-storey public building, shown in Figure 1, and its further use for verification of compliance with fire safety requirements. The fire occurred in the building addressed in the manuscript. The owner conducted an appraisal to identify violations made by the management company that was responsible for the 2018 restructuring. All cladding must be treated by the method of pressure impregnation and have flammability and combustibility ratings B1 and G1. But, the owner was unable to provide the required number of specimens to conduct complete tests.



Figure 1. General view of a building under reconstruction.

2. Materials and Methods

According to the technical manual, a suspended façade system has vertical and horizontal rails and brackets made of galvanized steel. Dowels are used to fix them to the walls. Building walls are insulated with 150 mm-thick non-combustible mineral wool, fixed by disk-shaped dowels. Timber panels made of pine planken, 1200 × 160 × 20 mm each, serve as cladding elements. The panels are fastened to the substructure by galvanized self-tapping screws made of corrosion-resistant steel. Façade cladding is made of timber panels; the architectural design of the façade is shown in Figure 2. The suspended façade and fixing systems are shown in Figure 3. Window and door casing elements are made of galvanized steel to ensure fire safety.

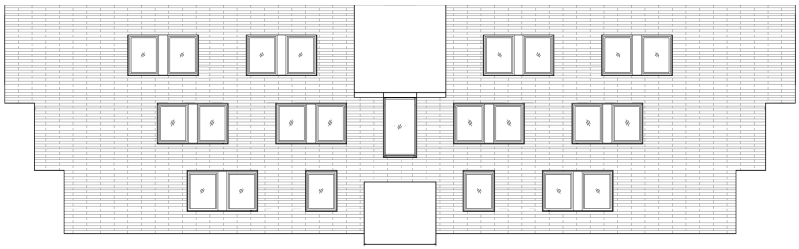


Figure 2. Architectural design of the building façade.

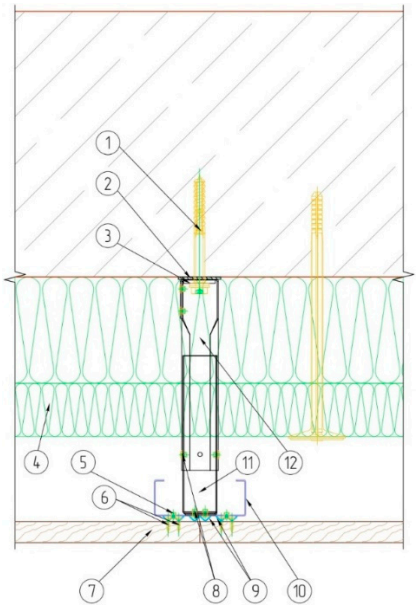


Figure 3. The suspended façade fastening system: 1—fastening anchor, 2—paronite gasket, 3—washer, 4—mineral wool insulation, 5—rivet, 6—self-tapping screw, 7—pine planken, 8—rivet, 9—planken fastener, 10—vertical rail, 11—bracket extension, 12—bracket.

This work hypothesizes that information on essential thermolysis characteristics of layers of the material allows prognosticating their performance under fire conditions.

The following tasks were to be accomplished within the framework of this research project:

- analyzing and selecting research methodologies;
- choosing essential thermo-analytical characteristics of the surface layer and inner layers of fireproof timber specimens;
- using the results of earlier studies and values of thermo-analytical characteristics to predict the ignition resistance of elements of timber cladding for façades, including the surface density of the incident heat flux that can trigger ignition;
- conducting a rapid flammability test to analyze the prognosticated flammability characteristics of timber.

The following timber fireproofing evaluation methods were analyzed to select the research methodology: a control method for checking the fireproofing effectiveness and a quality control method for fireproofing [38]; a method for rapid testing of fireproofing effectiveness [39]; FTIR spectroscopy used in fire investigations to analyze residues of flame retardants in the material [40], and a method of thermal analysis [41].

Methods of fireproofing efficiency control [38,39] consist in detecting combustion retardants by identifying the mass loss in pine timber specimens. These methods cannot identify fire retardant application techniques. In addition, specimens, needed to find the fireproofing effectiveness, must be manufactured as 150 × 60 × 30 mm bars, uniformly treated with flame retardant on all sides, which is impossible in this case. The specimens provided for testing were 20 mm thick, which is less than what is required for standard tests, and the fireproofing substance, needed to treat standard specimens, is unavailable. FTIR spectroscopy will show the presence of flame retardant but provide no information about the impregnation method.

Research into the effectiveness and identification of various flame retardants proves that objective data on the fireproofing of timber and timber materials can be obtained by studying individual stages of the thermal degradation process using thermal analysis [42–44]. However, these works fail to analyze other methods of fireproofing. However, in their earlier work [45] the authors of this paper evidence that compared results of the thermal analysis of timber specimens, extracted from different layers of the material, provide information about the application of surface or pressure impregnation.

Four pine planken specimens, (350–500) × 160 × 20 mm each, were extracted from different parts of the façade cladding, repaired in 2018. Technical manuals have no information about the fire retardant, its application methods, and effective period. Hence, the task of the research is to check the effectiveness of the timber façade fireproofing and the method of the fire-retardant application. The external view of the planken specimens, used for testing purposes, is shown in Figure 4.



Figure 4. Planken specimens submitted for the research purposes.

Specimens 1 and 2 had a heterogeneous surface with small cracks; they had no traces of biological damage. The surface of specimen 1 had gray inclusions (presumably, the remains of cement); specimen 3 had a heterogeneous surface with deep cracks; the cut and end faces of this specimen had traces of biological damage; specimen 4 had a homogeneous surface with surface cracks.

Thermal analysis served as the research method, used to (1) detect the presence of flame retardant in timber and (2) find the method of its application. Comparative

experiments were conducted to detect the presence and check the effectiveness of flame retardant in the surface and inner layers of timber planken specimens.

Cutting tools were used to extract specimens both from the timber surface and its layers located at a depth of 8–9 mm to conduct research using pine planken specimens 1–4. Hence, eight specimens were made to study the thermal decomposition of fire-retarded timber. The location of specimens in timber and their numbering are shown in Table 1.

Table 1. Breakdown of planken specimens used to conduct thermal analysis.

Specimen Number	Point of Specimen Extraction
$1_{surface}$	Specimen surface
1_{inner}	At a distance of 8–9 mm from the specimen surface
$2_{surface}$	Specimen surface
2_{inner}	At a distance of 10 mm from the specimen surface
$3_{surface}$	Specimen surface
3_{inner}	At a distance of 8–9 mm from the specimen surface
$4_{surface}$	Specimen surface
4_{inner}	At a distance of 8–9 mm from the specimen surface

Primary samples (5 items) were extracted from different points of the submitted specimen in approximately equal quantities. An average specimen was prepared for testing, which was the amount of material extracted from the primary sample. Three micro-specimens were prepared from the average specimen for thermal analysis testing. Table 2 shows the average results for the 3 tests of average specimens.

Table 2. TGA results.

Specimen Number	Weight Loss, %, in the Temperature Range, °C		Residual Coke, %	Main Peak	
	30–150	150–400	at 400 °C	T_{max}, °C	A_{max}, %/min
$1_{surface}$	6.7	66.7	33.3	360	21
1_{inner}	9.0	82.9	17.1	360	24
$2_{surface}$	5.4	53.3	46.7	261	12
2_{inner}	9.2	73.8	26.2	350	24
$3_{surface}$	8.5	83.5	16.5	347	24
3_{inner}	8.2	84.9	15.1	362	32
$4_{surface}$	4.5	49.6	50.4	241	13
4_{inner}	4.6	51.1	48.9	245	12
Untreated pine timber	5.9	71.6	28.4	345	29

Thermal analysis was conducted using Setsys Evolution («SETARAM Instrumentation», Caluire-et-Cuire, France), a universal thermal analyzer. TGA (thermogravimetric analysis) and DTG (derivative thermogravimetry) research methods were used. TGA and DTG analyses identified a dependence between (1) the mass and the specimen mass-loss rate and (2) the heating temperature. A nitrogen blanket was used to conduct the test at a heating rate of 20 °C/min in the temperature range of 30–800 °C.

The following characteristics were traced in the course of analysis of thermal curves: the specimen mass loss, the coke residue, the temperature, and the mass-loss rate for the main peak. Mass loss indicates dehydration in the temperature range of 30–150 °C, deterioration of the material, and coking in the temperature range of 150–400 °C (the main

peak on the curve). The coke residue was traced at a temperature of 400 °C. The maximum mass-loss rate A_{max} and temperature T_{max} are shown for the main peak on DTG curves for all specimens at the temperature of 250–350 °C.

Due to the insufficient number of specimens needed to study the resistance of timber to the effect of incident heat flux according to the standard methodology, a rapid testing method was developed [45,46]. This rapid testing method is based on the principle underlying the standard methodology. An ignitability tester, designated for construction products exposed to radiant heat flux and open flame coming from an ignition source, was used to conduct a rapid test [45,46]. Relevant thermo-analytical characteristics and values of the critical surface heat flux density (CSHFD), obtained earlier for different flame-retardant compositions [33,44], were used to prognosticate values of CSHFD, which could trigger the ignition of specimens. For a rapid test, 160 × 160 mm test specimens were made from each specimen of timber, and the face side of planken boards served as the exposed surface.

Before testing, specimens were conditioned at the temperature of (23 ± 2) °C and relative humidity of (50 ± 5)% for 48 h. Mass loss measurements were taken to a precision of 0.8%; temperature measurements were taken to a precision of 1.5%. The uncertainty of mass loss and mass-loss rate measurements was 5%, taking into account random and systematic errors; the uncertainty of temperature measurements was 3.5% at a confidence level of 0.95.

Hence, the proposed methodological approach to predicting the flame resistance of specimens, needed to check their usability as timber cladding for façades, has the following steps:

- finding certain relevant thermo-analytical characteristics of timber specimens to draw conclusions about the presence of flame retardant and the fireproofing method;
- analyzing earlier findings, aimed at evaluating the effectiveness of fireproofing of timber products and predicting the flame resistance of specimens;
- conducting a rapid test to verify the value of CSHFD that triggers the ignition of specimens under study;
- conducting a rapid test to verify the usability of flame-retarded timber as the cladding for façades.

3. Results and Discussion

Effective flame retardants were applied in combination with versatile timber treatment methods (surface and pressure impregnation) to make materials featuring different combustibility and flammability parameters. The experimental data of thermal analysis, and their comparison with results of standard combustibility and flammability tests, revealed the main thermo-analytical criteria of fire resistance (impregnation efficiency): carbonized residue (coke); amplitude of the II-th peak of a DTG curve (maximum rate of thermal oxidation of the material); temperature at which the rate of thermal oxidation is maximal. Pine timber fireproofed by the method of pressure impregnation ignites at CSHFD of 32.5 kW/m^2 and has the following relevant thermo-analytical characteristics for surface and inner layers: coke residue (50 ± 5)% at 400 °C; and the maximum rate of thermal oxidation of the material is in the range of 240–260 °C and is (12 ± 5)%/min [44].

Specimens, made of timber planken boards, were studied to find relevant thermo-analytical characteristics, presented in Table 2 and Figures 5–10. For the purposes of comparison, thermo-analytical characteristics of untreated pine timber are provided according to [43].

The analysis of the thermogravimetric study of timber specimens 1–4 (Figures 5–10), shows that timber decomposes in the following temperature ranges:

(1) 30–150 °C—the process of timber dehydration;
(2) 150–400 °C—the protective effect of proofing substances, as well as the process of decomposition of the main components of timber (hemicellulose, cellulose, lignin) and formation of the coke layer;
(3) 400–600 °C—the process of gradual burnout of the coke layer, taking into account its thermophysical characteristics; ash residue formation.

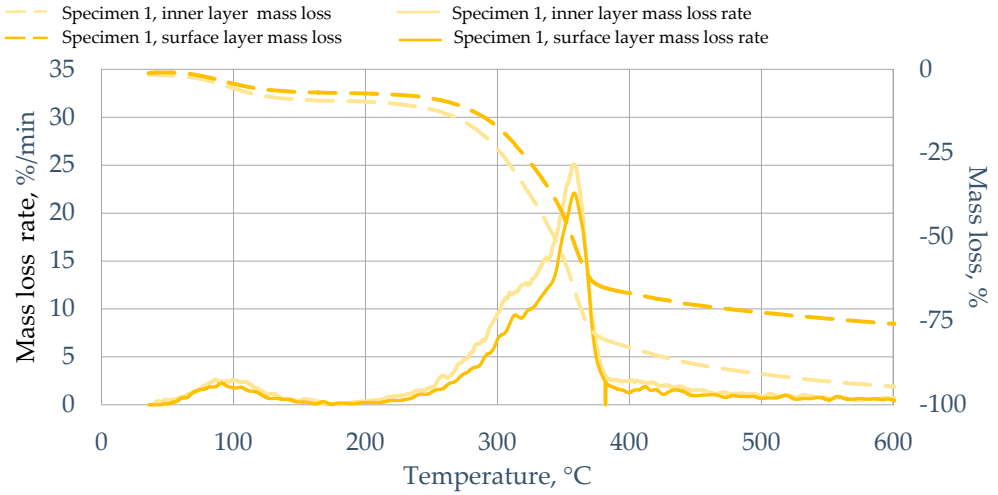


Figure 5. Specimen 1. Dependence of the mass loss and the mass-loss rate in specimens on heating temperature.

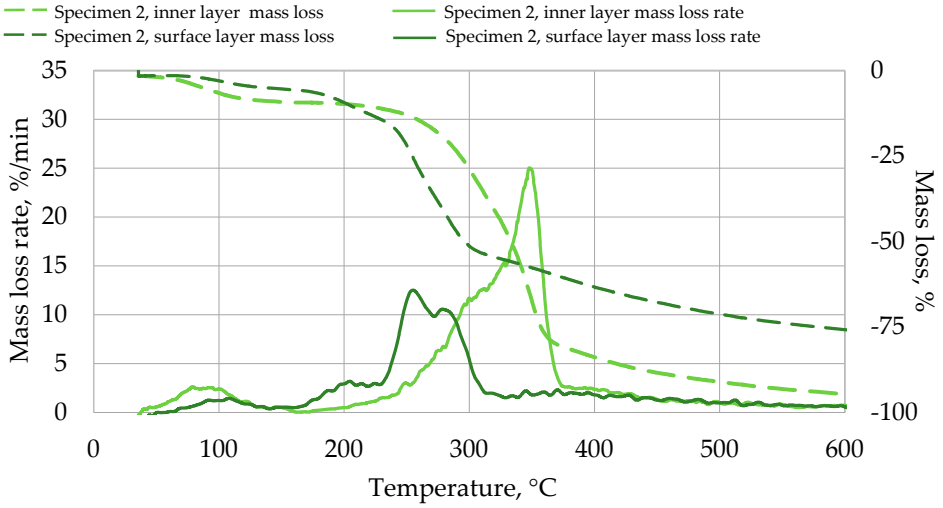


Figure 6. Specimen 2. Dependence of the mass loss and the mass-loss rate in specimens on heating temperature.

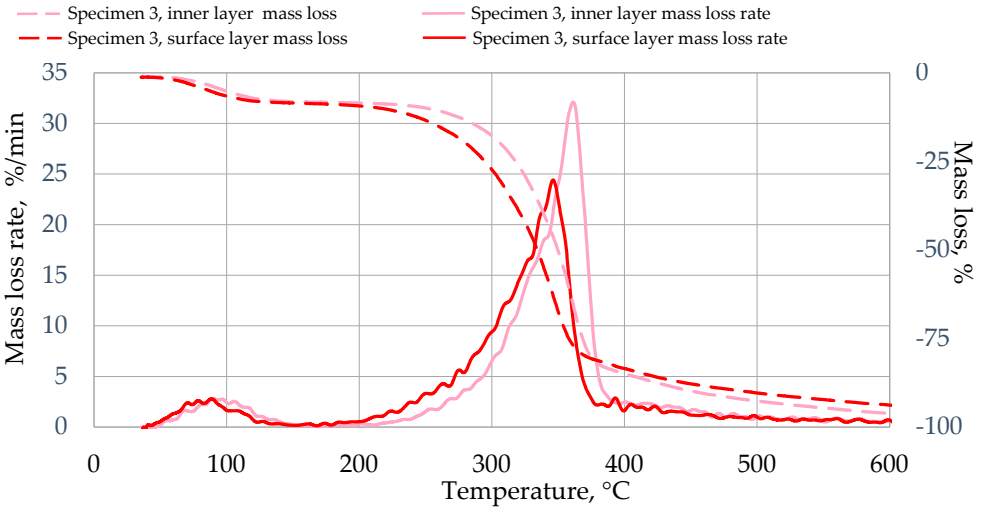


Figure 7. Specimen 3. Dependence of the mass loss and the mass-loss rate in specimens on heating temperature.

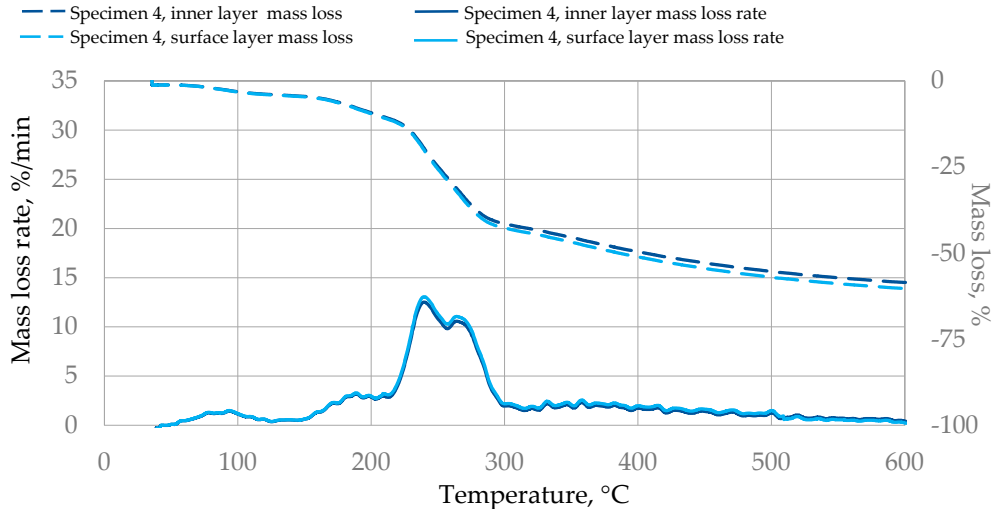


Figure 8. Specimen 4. Dependence of the mass loss and the mass-loss rate in specimens on heating temperature.

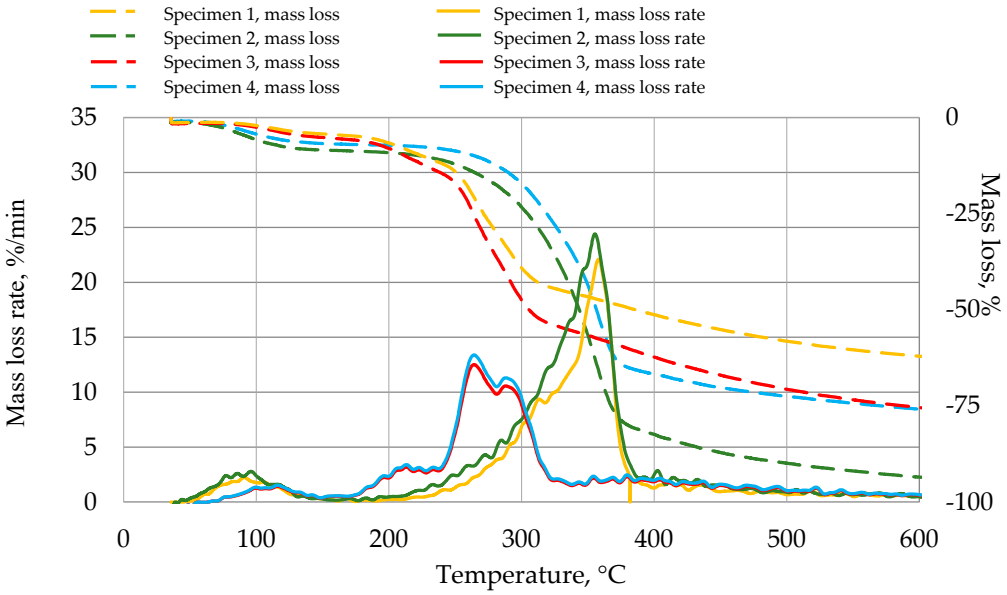


Figure 9. Specimens 1–4. Dependence of the mass loss and the mass-loss rate in surface layer specimens on heating temperature.

Well-known effects produced by the majority of flame retardants are (1) the onset of pyrolysis at a lower temperature, (2) more intensive pyrolysis, and (3) carbonized residue produced as a result of pyrolysis, where (4) the emission of combustible gaseous substances, triggering flame combustion, is suppressed. At the same time, fireproof wood has A_{max} less than 20%/min [42–44].

Dependences, shown in Figures 9 and 10, demonstrate a difference in the thermal degradation of surface and inner layers of the studied specimens featuring different extents of fireproofing.

This methodological approach was developed by the authors on the basis of earlier studies [33,44] and applied to pine timber treated with fire-bio-protective impregnating agents (a complex of substances including phosphoric acid derivatives, ammonium salts, and various synergistic additives). A correlation was found between flammability parameters and thermal analytical characteristics for timber treated with impregnation compositions. This information serves as the basis of the presented approach.

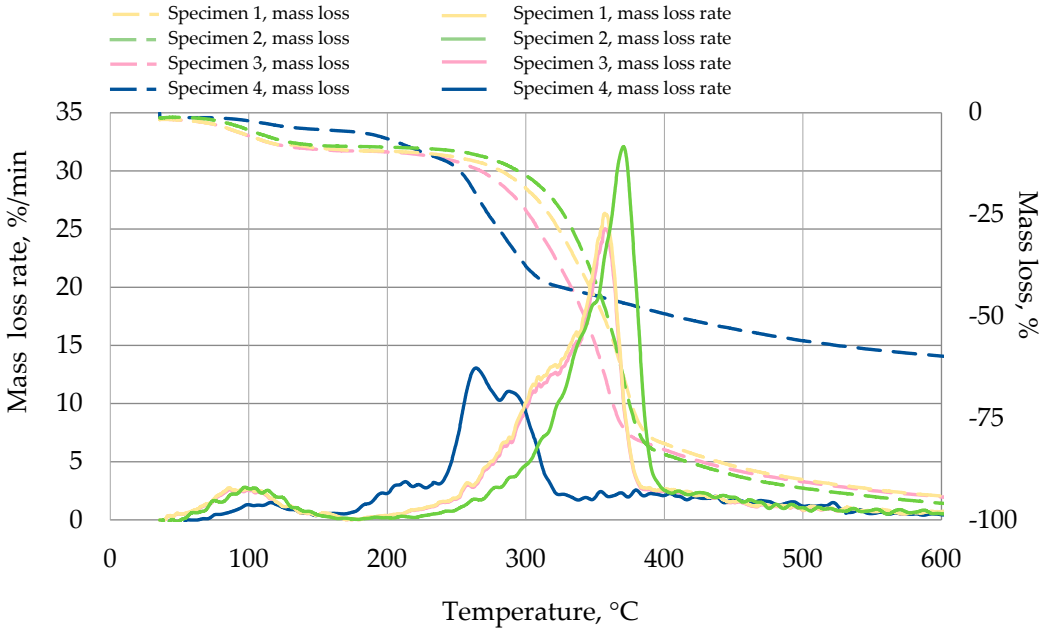


Figure 10. Specimens 1–4. Dependence of the mass loss and the mass-loss rate in inner layer specimens on heating temperature.

Values of the incident heat flux density (heat flux density (q), at which the ignition of specimens can occur within 900 s) were substantiated for a rapid test. The authors' earlier findings of properties of the fire hazard of flame-retarded timber [33] were used for this purpose.

As it follows from the dependencies, shown in Figure 5 for specimen $1_{surface}$ and specimen 1_{inner}, the maximum mass-loss rate was recorded at a temperature of 360 °C. Values of (1) the rate of mass loss and (2) the total mass loss in the material of the inner layer of a planken board approach values characteristic of untreated timber, while residual coke and the total mass loss in the surface layer is much lower, which suggests the presence of inorganic non-combustible impurities in the specimen, such as cement dust, identified in the course of the initial visual inspection of the specimens.

The surface layer of specimen 2 shows a large shift in temperature and the maximum mass-loss rate (261 °C) during thermal decomposition. The maximum mass-loss rate in the surface layer is two times lower than that in the inner layer, and the residual coke in the surface layer is 1.8 times larger than the residual coke in the inner layer, which indicates the presence of a flame retardant applied by the method of surface treatment (impregnation).

A shift in the peak of the DTG curve affects timber specimen $2_{surface}$: temperatures go down (by 90 °C), and this process is accompanied by a simultaneous decrease in the mass loss at the second stage of thermal degradation, which means predominance of the dehydration pattern of thermolysis underway in the presence of fireproofing compositions and products of their decomposition accompanied by the formation of residual coke [44].

As for timber specimens $3_{surface}$ and 3_{inner}, all thermo-analytical characteristics are typical for similar parameters of untreated timber, while the maximum mass-loss rate in the inner layer is much higher, which may be due to the presence of biological damage resulting in deep cracks identified during initial inspection.

The surface and inner layers of specimen 4 demonstrate a great shift in temperatures of the maximum mass-loss rate (241–245 °C), with the maximum mass-loss rate itself being more than two times lower than that in untreated timber, and with residual coke in both layers being 1.8 times higher than that in unprotected timber, indicating the presence of a flame retardant applied using the pressure impregnation method [44].

Hence, comparative data on the presence of a flame retardant, its effectiveness, and method of application to timber were obtained by a layer-by-layer analysis of thermal

decomposition characteristics of pine planken specimens within the framework of a study of the process of thermal degradation.

Earlier studies, conducted by the authors [33,44] to analyze the fire hazard properties of flame-retarded timber, evidence that pine timber treated with a similar chemical composition of compounds of fire-bio-protective impregnating agents (a combination of substances, including phosphoric acid derivatives, ammonium salts, and various synergistic additives), using the method of surface treatment, belongs to the first group of flame-retardant efficiency (its mass loss is below 9.0% according to [38], has a value of critical surface heat flux density (CSHFD) in the range of 15–18 kW/m^2 [45,46], and belongs to group G3 materials [29]. In this case, flammability parameters, including T_{max} = 315–330 °C, ΔL = 78–85%, Δm = 37–45%, and τ = 103–290 s, correspond to class E [30].

Tests were conducted to determine the flammability class [28,47]. For each test, 12 specimens with a length of 1000 mm and a width of 190 mm are made. The specimens are placed in a holder composed of four rectangular frames arranged vertically. In the course of testing, specimens are exposed to the fire coming from the flame of a gas burner. The following parameters are determined for each test:

- the flue gas temperature, T_{max};
- the time of independent combustion and (or) smoldering, τ;
- the length of the specimen damage, ΔL;
- the difference between the mass of the specimen before and after the test, Δm.

A special composition of integrated flame retardants, applied using the method of pressure impregnation of timber, allowed obtaining materials whose CSHFD was 32.5 kW/m^2 and whose flammability group was G1 (their flammability parameters were T_{max} = 130 °C; ΔL = 52%; Δ_m = 3%; τ = 0 s), which corresponds to fire hazard class B [30].

In the course of a rapid test conducted to find flammability at pre-set values of the incident heat flux density, specimens 1 and 3 demonstrated properties characteristic of untreated timber (confirmed by the results of thermal analysis): specimen 2 ignited at q = 17.5 kW/m^2 (these data are typical for timber subjected to the surface treatment with a flame-retardant composition); specimen 4 ignited at q = 35 kW/m^2, which means that it can be attributed to flammability group B1 [45,46] and flammability group G1 [29], corresponding to fire hazard class B [30].

A comparison of these data evidences with a high degree of probability that the hypothesis about the predictability of fire resistance of flame-retarded timber, based on relevant thermo-analytical characteristics, is confirmed.

Comparing the obtained data, it can be stated with a high degree of probability that the hypothesis about the possibility of predicting the resistance to ignition of fire-protected timber, based on relevant thermo-analytical characteristics, was confirmed.

As for the finishing timber materials designated for façade systems, thermo-analytical studies and information about relevant characteristics of thermolysis of material layers allow predicting their behavior under fire conditions, assuming that the current requirements applied to resistance to heat flux and flame retardance are taken into account (flammability group B1 [45,46] and flammability group G1 [29]).

Relevant thermo-analytical characteristics and a rapid test conducted to check the ignition of specimens of a timber planken façade system, as well as the comparative analysis of the experimental data, substantiate the following conclusions:

- specimen 1 was not subjected to any flame-retardant treatment; its fire hazard characteristics do not meet the requirements of regulatory documents;
- specimen 2 was subjected to the surface treatment with a flame retardant; its fire hazard characteristics do not meet the requirements of regulatory documents;
- specimen 3 was not subjected to any flame-retardant treatment, and it is unsuitable for further use at a construction site due to the presence of deep cracks and biological damage;
- specimen 4 was subjected to flame-retardant treatment using the method of pressure impregnation; its fire hazard characteristics meet the regulatory requirements, and it can be used as façade cladding.

4. Conclusions

The studies achieved the following:

- identified the main (relevant) thermo-analytical criteria of fire resistance of timber impregnated with combustion retardants using various impregnation methods;
- were conducted to develop a methodological approach to checking the effectiveness of flame retardants for timber products and methods of their application based on the study of relevant thermo-analytical characteristics;
- were conducted to predict such fire hazard properties as flammability and combustibility of flame-retarded timber impregnated with flame retardants at a construction site in furtherance of comparative thermo-analytical criteria of its thermal decomposition;
- revealed that the novel methodological approach can be applied to tackle issues of fireproofing efficiency control in respect of pine façade structures treated with impregnation substances.

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