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Abstract. There are many studies on the thermal treatment of wood, but the treatment of thermally modified wood with different flame retardants, and the changes that occur in this process are not fully understood. This paper assesses various thermal modifications and the flame retardant effect on thermally modified wood under conditions that simulate the natural process of wood combustion by a heat source, constant air flow and exhaust gas flow. The research temperature ranges from 160 to 260° C. It has been experimentally proven that thermally modified wood impregnated with a fire retardant has a greater fire and ignition resistance than untreated wood.

1. Introduction
Wood is one of the most stable, aesthetically pleasing and environmentally friendly materials. The demand for wood and wood products has been increasing in recent years. Among construction materials, wood has the best machining ability, which allows its realization in wooden constructions in hard-to-reach places. The material is used both outside and inside wooden constructions.

However, because of its easy flammability, it often contributes to the formation of fires. Therefore, the use of wood is restricted by different requirements and fire safety regulations.

To improve fire resistance, wood is usually treated with fire retardants.

Currently, the level of production of wood products with improved flame retardant characteristics does not meet the growing demand for them. Some fire protection technologies for wood have been in use for almost two thousand years.

Due to the growing environmental problem as well as the concern for the safety of consumers of flame retardant products, the traditional use of boron and formaldehyde is likely to decrease.

1.1. Literature review
Research on thermo-modifying wood processing has been carried out since the early 20th century. Despite this long history, the development of thermo-modified wood was only commercially successful in Europe in the 1990s. The growth of the market for thermally modified wood in Europe was in part due to limited regulation of the use of toxic chemical treatments to protect wood from biological attack and biodegradation.

In Russia and the United States the market for thermally modified wood is entering a new round of development. In Russia, potential demand for thermally modified wood from domestic sources may be caused by, among other things, consumer demand for non-chemical products and regulations prohibiting the import of illegally harvested wood. These factors may allow thermally modified wood to become a leading substitute for imported tropical wood and pressure-treated lumber.

Experimentally - fundamental works in the field of fire hazard and fire resistance of construction objects (including wooden) in different periods were engaged in domestic and foreign scientists, such as: Romanenko I G, Roitman V M, Strakhov V L, Herashchenko A N, White R H, Babrauskas V, Takeda H, Janssen's M L, Konig J, Mehaffey J R et al.[1-6].

In the field of wood fire protection the works of Leonovich A A, Pokrovskaya E N, Taubkin S I, Serkov B B, Sivenkov A B, Aseeva R M, Ostman B, Dietenberger M A, Kozlowski R, etc. are taken into account. [7-11]. The influence of thermal modification on anatomical, mechanical, physical, biological and chemical properties of wood has been the subject of many studies, however, there is no information about the fire characteristics of this material in scientific literature [12].

2. Materials and methods

Methods of improvement that change the basic properties of the material are called modification methods. Interest in thermally modified wood has recently increased significantly [13, 14]. This interest is due to the reduction in production of durable wood materials, increased interest in durable building materials and legislative changes that limit the use of toxic substances in wood-based materials.

The tested samples of thermally modified spruce wood 200 mm (longitudinal cut), 100 mm, 20 mm were thermally modified and divided into two groups, one of the groups was treated with fire retardant. Samples of thermally modified spruce wood at temperatures between 20°C and 160°C; 180°C and 210°C were labelled as P (samples P-160, P-180 and P-210) and the second group of flame retarded spruce wood was labelled as S (S-20, S-160, S-180 and S-210) (figure 1).

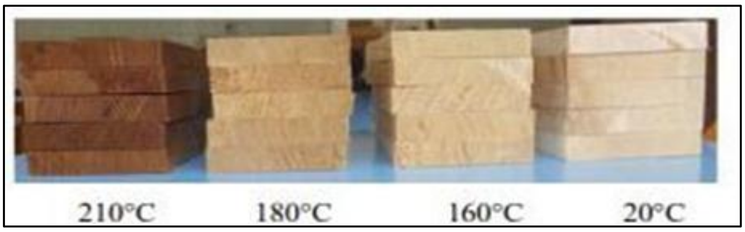

Figure 1. Test specimens (S-210, S-180, S-160 and S-20).

The thermal modification process was performed as follows (table 1):

1) Heating and drying - at this stage the temperature in the furnace was set to around 100°C to maintain the steam action. It was then increased to 130°C. Drying is hot air or hot steam. Throughout this stage the wood was dried to approximately zero humidity [15].

2) Thermal modification - at this stage the temperature was raised to 185° C-230°C for 2-3 hours.

3) Cooling and air conditioning - in the third stage, thermally modified wood was gradually cooled to a temperature of 80°C - 90°C and humidity was stabilized so that its final level was normal 4-7%.

Table 1. Process Input parameters and thermal modification process parameters.

	Process Input parameters		
Wood moisture	between 2 and 4%		
Volume of filled furnace	0.8 m^3		
Maximum temperature	210 ° C		
	Thermal modification process parameters		
	160° C	180° C	210° C
Heating	6.3 hours	4.5 hours	4.8 hours
Thermalization	4.4 hours	5.3 hours	6.7 hours
Cooling	1.7 hours	2.4 hours	4.2 hours
Total modification time	12.4 hours	12.2 hours	15.7 hours

The average density values of the test specimens are shown in table 2. FLAMGARD TRANSPARENT flame retardant was applied to the samples. It is a viscous coating that becomes transparent with a light yellowish tint after drying. During the combustion process, a thick, non-combustible layer of thermal insulating foam appears on the surface of the treated material, causing time delays and thus reliably protecting the material against fire and radiation heat source. In this study, a two-stage test of a new combustion evaluation method was conducted. The first stage consisted in direct exposure of the test sample to a gas burner for up to 10 minutes. The test sample was placed under the burner at an angle of 45°. The flame was 10 cm from the mouth of the burner and was located in the centre at the bottom of the sample (see figure 2).

Table 2. Average densities of test specimens.

Thermal modification		20° C	160°C	180° C	210°C
P	Density (kg/m3)	447	445	452	430
	Moisture Content (%)	2.9	2.8	2.8	2.8
S	Density (kg/m3)	453.8	461	461.2	469.2
	Moisture Content (%)	2.8	2.8	2.9	2.8

Figure 2. Test equipment.

The distance from the mouth of the burner to the centre of the sample was 9 cm, in the second stage (after 10 min) the flame was removed from the sample and the weight loss and burning rate was controlled for another 5 min.

Thermal degradation may continue in the luminous layer of wood, resulting in self- ignition and sustainable charring. This evaluation method is designed to simulate the process of natural wood combustion by a flame source, sustainable air supply and free flow of combustion gases. A laboratory device was used to simulate this process. The device consisted of: a through burner USBEC 1011/1 (DIN-DVGW reg. NG- 2211AN0133, blasting, 1.7 kW, Dresden, Germany), a propane tank, an electric scale (MS 1602S / MO1, Mettler Toledo, Geneva, Switzerland) and the Balance Link 4.2.0.1 software to record the wood weight.

During the wood flammability test, the weight loss of test specimens during continuous weighing was recorded at regular intervals of 10 seconds. The average burning rate and weight loss were calculated using appropriate equations (1) and (2). The data obtained were evaluated using the Excel software.

3. Results and Discussion

Weight loss and combustion rate were assessed by two criteria (1) and (2).

The weight loss was calculated by a formula:

$$\Delta m = (m_1 - m_2) \cdot 100\,, \tag{1}$$

where, Δm - weight loss (%), m_1 - weight of the sample before the test (g), m_2 is the mass of the specimen after the test.
The combustion rate was calculated using the equation:

$$v = (m_t - m_t + 10)/(m_{t0} \cdot 10), \tag{2}$$

where, v - combustion rate (% / s), m_t- weight (gr) in time t, $m_t + 10$ - sample weight (g) 10 s later, m_{t0} - weight (gr) of the sample at time 0.

The results of the experiment show the difference between thermally modified spruce wood treated with fire retardant impregnation and untreated wood (table 3).

Table 3. Evaluation of the main statistical characteristics of the influence of heat treatment and retarder on the values of controlled characteristics.

The effect is	Sum of squares	Degrees of freedom	Rejection	Fisher F-test	Level P value
Weight Loss Δm (%)					
Free temperature	612948	1	612948	273.631	0.000
Thermal modification	6.122	3	2.041	0.911	0.447
Slow down	8319	1	8319	3,714	0.063
Thermal modification and deceleration	5476	3	1825	0.815	0.495
Error	71.682	32	2.240		
Maximum burning speed (% / s)					
Free temperature	38041.757	1	38041.757	67.660	0.000
Thermal modification	985.949	3	328.650	0.585	0.630
Slow down	11984.059	1	11984.059	21.315	0.000
Thermal modification and deceleration	755.664	3	251.888	0.448	0.720
Error	17991.940	32	562.248		
Time to reach maximum burning speed (s)					
Free temperature	2083010	1	2083010	209.646	0.000
Thermal modification	27465	3	9155	0.921	0.442
Slow down	30914	1	30,914	3.111	0.087
Thermal modification and deceleration	61409	3	20.470	2.060	0.125
Error	317947	32	9936		
Ratio of maximum burning speed (%)					
Free temperature	3.898	1	3.898	6.139	0.019
Thermal modification	2.336	3	0.779	1.226	0.316
Slow down	1.898	1	1.898	2.989	0.093
Thermal modification and deceleration	1.180	3	0.393	0.619	0.608
Error	20.317	32	0.635		

Weight loss was the first non-standard assessment criterion.

The lowest weight loss - 2.25% - was recorded for thermally modified spruce wood combined with flame retardant at 210°C compared to heat-treated wood without flame retardant coating (4.31%). The difference in weight loss between the two types of modifications is about 2%.

This is followed by thermally modified flame retardant wood at 180°C with a weight loss of 3.78% and 160°C with a weight loss of 3.88%. Unmodified spruce wood in combination with fire retardant has a weight loss of 4.72% after 10 minutes from the beginning of the experiment, you can see the difference between samples treated with fire retardant and untreated with it (table 4).

Table 4. Fire resistance values of treated spruce wood (S) and untreated spruce wood (P).

Thermal modification	20°C	160°C	180°C	210°C
P	4.72	3.98	4.48	4.31
S	4.40	3.88	3.78	2.25

The fire retardant increases the ability to withstand fire and ignition of thermally modified spruce in the event of a fire. This result also confirms the statistical estimate of weight loss of thermally modified spruce wood when comparing treated and untreated wood samples (see figure 3).

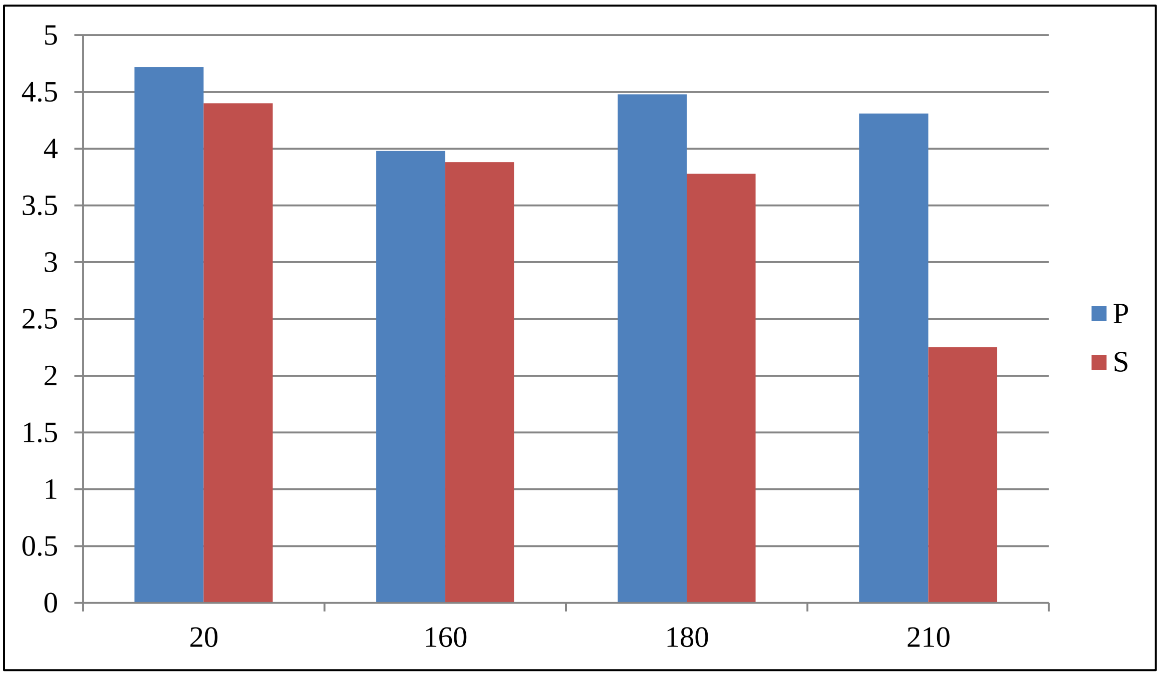

Figure 3. Comparison of weight loss of thermally modified spruce wood with thermally modified fireproof spruce wood.

Table 5 shows the results estimating the effect of thermally modified wood on the controlled characteristics. Based on the level of significance "P", we can conclude that the degree of heat treatment of wood showed statistically significant effects only on the values of observed characteristics. Loss of weight in other cases did not have a significant effect on the controlled characteristics.

Table 5. Combustion rate values of a thermally modified flame retarded spruce sample (S) and a thermally modified untreated spruce sample (P).

Thermal modification	20°C	160°C	180°C	210°C
P	18.9	17.78	34.08	36.81
S	12.40	12.56	15.36	6.15

The second evaluation criterion is the combustion frequency [14, 15]. The values correspond to the weight loss results and are the evaluation criterion (see table 5). The highest combustion rate was observed for thermally modified spruce wood not treated with fire retardant at 210°C. On the other hand, the lowest burning rate and absence of spontaneous combustion at 210°C were observed for thermally modified spruce wood not treated with fire retardant. In this case, fire retardant and its positive effect on thermally modified spruce wood was significant. And untreated spruce - at 20°C, the increase in combustion rate occurred at the 10^{th} minute at the end of the exposure to the flame source and the combustion rate decreased.

In all cases, the effect of flame retardants is visible in terms of reduced burning speed (even with thermally unmodified wood the difference between treated flame retardants and untreated spruce wood is visible).

4. Conclusions

The experiment confirmed the suitability of an ignition method, a thermally modified spruce. This method is sensitive enough to assess the changes that the thermally modified wood has shown under different temperature conditions.

As can be seen from table 6, the difference in weight between coatings at different temperatures before and after drying is minimal. At 210°C it was less than 7 (g/m^2). Samples of thermally modified spruce at this temperature achieved the best results within our evaluation criteria.

The results show that thermally modified refractory wood, at any temperature, loses less weight than untreated spruce wood.

Table 6. Comparison of weight of fireproof coating in wet and dry condition.

Thermal modification temperature (°C)	Weight of coating at humidity (g/m^2)	Weight of coating after drying (g/m^2)	Dry matter (%)
20	103.65	67.42	65.04583
160	101.31	86.23	85.11499
180	110.04	97.31	88.43148
210	105.69	99.04	93.70801

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