Flammability Characteristics of Thermally Modified Oak Wood Treated with a Fire Retardant

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Flammability characteristics were determined for oak wood (*Quercus robur* L.), which was thermally modified at 160, 180, and 210 °C. Subsequently, the thermally modified and unmodified wood was treated with a fire retardant. The effect of the thermal modification (TM) and fire retardant treatment (FRT) on the weight loss (WL), burning rate (BR), maximum burning rate (MBR), and time to reach the maximum burning rate (TRMBR) were evaluated. The FRT had an expected positive effect on all of the flammability characteristics, where the WL, BR, and MBR decreased, and the TRMBR increased. The TM temperature did not have a clear effect. As the TM temperature increased, the WL and BR decreased. The highest differences were found at 160 and 180 °C. As the TM temperature increased for the wood without the FRT, the TRMBR decreased. During the burning of the thermally modified wood with the FRT, the trend was the exact opposite.

Keywords: Burning rate; Maximum burning rate; Weight loss; Thermal modification; Fire retardant; Oak

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INTRODUCTION

Wood is a natural material with many excellent properties (aesthetic and mechanical) that make it suitable for versatile use. Despite those properties, wood has certain disadvantages, such as a low resistance to biological agents (fungi, insects, *etc.*), changes to the physical and mechanical properties, and high flammability. A common method of protecting wood against most of these effects is thermal modification (TM).

TM is a newer type of wood modification. There are currently several types of TM, the principle of which is different depending on the medium and temperature used (Navi and Sandberg 2012). The most well-known types of TM are ThermoWood in Finland, Plato Wood in the Netherlands, oil-heat treatment (OHT) in Germany, and Les Bois Perdure and rétification process (Retiwood) in France (Esteves *et al*. 2011; Sandberg and Kutnar 2016). In addition to these common TMs, there are also lesser known TM processes that use superheated steam, such as Wood Treatment Technology (WTT) in Denmark and Firmolin technology in the Netherlands, or a partial vacuum, like Termovuoto in Italy (Ferrari *et al*. 2013). In general, TM can be defined as a process in which high temperatures ranging between 150 and 260 °C are applied to wood in an environment with different types of media (steam, nitrogen, oil, *etc*.) without chemical substances (Sandberg and Kutnar 2016). TM remarkably affects the basic components of wood. Cellulose and hemicellulose are polysaccharides found in the cell walls of wood.

Cellulose, which is responsible for the strength of wood fibers because of its high polymerization degree, is more resistant to heat (Pandey 1999). Hemicellulose is less resistant to heat, and its degradation leads to the most significant decrease in the mechanical properties of thermally modified wood (Osvald and Gaff 2017). Lignin has an aromatic structure and fills the spaces between the lignocellulosic fibers. It is responsible for the rigidity of the material and is the most resistant to heat of these three components (Cademartori *et al*. 2013). TM improves the dimensional stability, durability, hygroscopicity, weather resistance, and resistance to fungi (Jämsä *et al*. 2000; Candelier *et al*. 2013; Kačíková *et al*. 2013; Baysal *et al*. 2014; Kondratyeva *et al*. 2016). In contrast, TM, especially above 220 °C, noticeably reduces the mechanical properties, *e.g*. the modulus of rupture, hardness, and impact bending strength (Kamdem *et al*. 2002; Kačík *et al*. 2015).

Mechanical properties are, however, only one group that is important for wood products. Fire properties are also important because fire is one of the most critical physical degradation factors for wood (Lee *et al*. 2004; Mohebby *et al*. 2007; Jiang *et al*. 2010). The fire properties of common wood-based materials have been thoroughly explored. Although there are several studies that deal with the flammability and burning of thermally modified wood (Martinka *et al*. 2013; Xing and Li 2014; Čekovská *et al*. 2017a; Čekovská *et al*. 2017b), their fire properties have only been investigated to a limited extent. Thermally modified wood is susceptible to flames and burning (Delichatsios *et al*. 2003), but is still used for interior and exterior elements. TM releases volatile components from the wood and degrades lignin and polysaccharides, which are closely related to the flammability and burning properties of wood (Manninen *et al*. 2002). Hence, thermally modified wood contains less volatile flammable components, and the likelihood of it igniting and subsequently combusting is reduced (Martinka *et al*. 2013). The flammability of wood can be modified with fire retardants (Sogutlu *et al*. 2011; Lowden and Hull 2013).

Wood fire retardants affect the burning of wood by delaying the ignitability and flame spread, and reducing the heat release (Östman *et al*. 2001; Hagen *et al*. 2009). Fire retardants work on different principles, although most of them use several mechanisms at once (Pries and Mai 2013). Most often, fire retardants create non-combustible charcoal layers on the surface of the wood under the influence of temperature and physically inhibit oxygen access to the wood (Jiang *et al*. 2014; Merk *et al*. 2015). Fire retardants for wood use chemicals based on phosphorus, nitrogen, boron, and combinations of these elements (Wang *et al*. 2004; Gao *et al*. 2006; Marney *et al*. 2008). Fire retardants are applied through various methods. Vacuum pressure impregnation is highly effective because it gets the fire retardant into a considerable depth, but it is only suitable for structural elements, facing, and flooring materials before they are used. Soaking does not require complicated machinery and is suitable for fire retardants that are in solutions that can penetrate into wood. Coatings, which are suitable for existing structures and built-in elements, use coating substances that form an insulating layer after they dry.

This research studied the flammability characteristics of thermally modified and unmodified oak wood. Each group of samples was divided into two subgroups according to their fire retardant modification. A two-component Flamgard Transparent coating was used as the fire retardant. A burning test was used to evaluate the basic characteristics, including the weight loss (WL), burning rate (BR), maximum burning rate (MBR), and time to reach the maximum burning rate (TRMBR).

EXPERIMENTAL

Materials

Seventy-five-year-old pedunculate oak (*Quercus robur* L.), used in this study, was harvested from the Poľana region in central Slovakia, near Zvolen. Wood samples with the dimensions 20 × 100 × 200 mm were cut from the section located in the middle distance between pith and bark (Fig. 1). The samples were divided into two groups: the first group was thermally modified, while the second group was unmodified. Both groups contained two subgroups, one of which consisted of fire retardant-treated samples, while the other one contained samples that did not undergo the fire retardant treatment (FRT). All of the samples were dried in a drying oven ULM 400 (Memmert GmbH & Co. KG, Schwabach, Germany) at a temperature of 103 ± 2 °C until an oven-dry state was reached. This condition facilitated the TM, and also induced similar moisture contents in the samples without TM, which was important for comparison purposes.

Fig. 1. Oak samples

Procedures

Thermal modification (TM)

The wood samples were modified in a thermal chamber (S400/03, LAC Ltd., Rajhrad, Czech Republic). Three final temperatures, 160, 180, and 210 °C, were chosen for the wood modification. The TM used the ThermoWood principle developed by VTT (Finland), which takes place in a protective atmosphere, dispersed water in the air, to prevent overheating and burning. The TM of the wood was carried out in three basic phases (Table 1).

Table 1. Conditions and Parameters of the Thermal Modification

	Thermal Modification (TM) Temperature		
	160 °C	180 °C	210 °C
Heating	10.6 h	11.4 h	14.6 h
Thermal modification	3 h	3 h	3 h
Cooling	6.4 h	7.2 h	8 h
Total time	20 h	21.6 h	25.6 h

The first phase of the TM consisted of heating the wood. During this phase, the temperature gradually increased until the desired temperature (160, 180, and 210 °C) was reached. In the second phase, the final temperature was maintained for 3 h. This time was the same for all of the TM temperatures. The third phase was characterized by a gradual cooling. The temperature was gradually reduced to 40 °C so that the wood did not undergo temperature and humidity shock when the chamber was opened. Then, the samples rested for 3 h in the ambient environment. The densities of the samples are listed in Table 2.

Table 2. Density and Moisture Content of the Oak Samples

	Unmodified	Thermal Modification (TM) Temperature		
		160 °C	180 °C	210 °C
Density before TM (kg/m^3)	774	769	766	775
Density after TM (kg/m^3)	774	736	683	673
Original moisture content (%)	10.5	10.8	10.7	11.2
Moisture content after TM (%)	5.5	5.8	4.9	4.2

Fire retardant treatment (FRT)

A two-component fire retardant coating from Flamgard Transparent (Stachema a.s., Rovinka, Slovakia) was used. The first component is a foamable, water-soluble coating substance (a mixture consisting of ammonium phosphates, a foam forming agent, oxalic and acetic acid, and fire retardant additives) that was applied in three layers so that the total spread was at least 500 g/m^2. The second component is an acrylic cover lacquer S 1818, which was applied in a single layer with a spread of at least 80 g/m^2. Both components were applied with a brush according to the conditions specified by the manufacturer (Table 3). The curing of the individual layers took place at 20 °C.

Table 3. Properties and Application Conditions of the Fire Retardant Treatment

Component	pH	Density	Thinner Type	Wood Moisture Content	Content of Non-volatile Components	Application Ambient Temperature	Hardening Time
Coating substance	2 to 3	1.2 g/cm^3	hot water	10%	min. 62%	10 to 35 °C	12 h/layer*
Cover lacquer	-	0.97 g/cm^3	C 6000	-	31.5%	20 °C	4 h

* last layer must dry for 24 h

Methods

Determination of the flammability characteristics

The flammability test was based on the direct application of flame to the wood, according to ČSN 73 0862/B-2 (1991). In this study, the weight was measured continuously during the test. Therefore, the sample holder and stand were placed on a scale to measure the WL throughout the burning process (Fig. 2). A sample was placed in the holder at a 45° angle to the horizontal plane with the assessed surface facing down. The height of the propane burner flame was set to 10 cm. The burner was placed at the center of the sample (intersection of the diagonals) so that the distance between the mouth of the burner and center of the sample was 9 cm. Weight measurements were taken at 10-s intervals using a laboratory scale (MS 1602S, Mettler Toledo, Greifensee, Switzerland). The whole test lasted for 10 min (Fig. 3). In addition to the WL, the BR, MBR, and TRMBR were also determined. Each combination of TM temperature and FRT was represented by five samples according to ČSN 73 0862/B-2 (1991), so the whole study contained 40 samples.

Fig. 2. Burning test apparatus

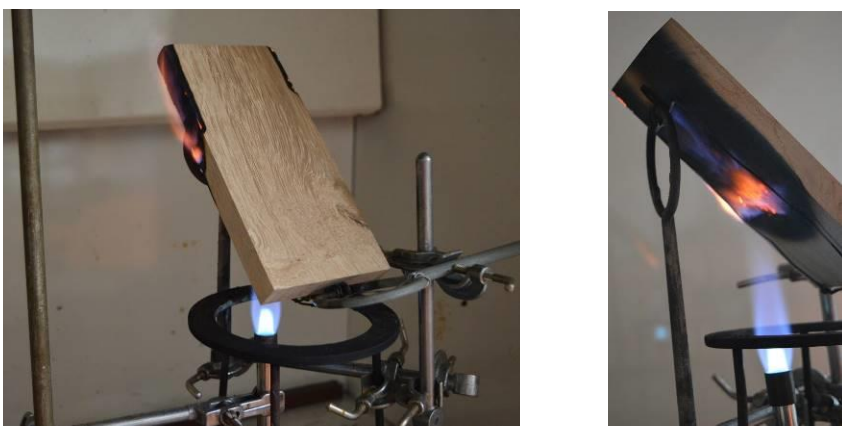

Fig. 3. Oak sample during the burning test

Evaluation and calculation

The effect of the factors on the flammability characteristics were assessed with Statistica 13 software (Statsoft Inc., Tulsa, OK, USA) by analysis of variance (ANOVA).

The wood density was determined before and after the TM according to ISO 13061-2 (2014). The moisture content was determined according to ISO 13061-1 (2014). Drying to an oven-dry state was also carried out according to ISO 13061-1 (2014).

The WL was calculated according to ČSN 73 0862/B-2 (1991) with Eq. 1,

$$m = \frac{m_0 - m_1}{m_0} \times 100 \tag{1}$$

where m is the WL (%), m_0 is the weight of the sample before the test (g), and m_1 is the weight of the sample at a certain time interval (every 10 s as well as after 10 minutes) (g).

The burning rate was calculated with Eq. 2,

$$v = \frac{m_t - m_{t+10}}{m_{t_0} \times 10} \times 100 \tag{2}$$

where v is the burning rate (%/s), m_t is the weight of the sample at time t (g), m_{t+10} is the weight of sample 10 s later (g), and m_{t0} is the weight of sample at time 0 (g).

RESULTS AND DISCUSSION

The statistical evaluation of the effects from the factors and combination of factors on the flammability characteristics of the oak wood are listed in Table 4.

Table 4. Effect of the Factors on the Flammability Characteristics

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F - Test	Significance Level P
Weight Loss					
Intercept	3,246.213	1	3,246.213	1,045.588	0.000000*
Fire retardant treatment (FRT)	707.575	1	707.575	227.906	0.000000*
Thermal modification (TM)	110.173	3	36.724	11.829	0.000022*
FRT × TM	114.298	3	38.099	12.272	0.000017*
Error	99.350	32	3.105		
Burning Rate					
Intercept	3,995.002	1	3,995.002	129.1936	0.000000*
FRT	837.683	1	837.683	27.0896	0.000011*
TM	157.731	3	52.577	1.7003	0.186646
FRT × TM	318.824	3	106.275	3.4368	0.028347*
Error	989.523	32	30.923		
Maximum Burning Rate					
Intercept	44,906.75	1	44,906.75	518.4761	0.000000*
FRT	11,060.61	1	11,060.61	127.7016	0.000000*
TM	1,604.85	3	534.95	6.1763	0.001963*
FRT × TM	467.08	3	155.69	1.7976	0.167491
Error	2,771.62	32	86.61		
Time to Reach the Maximum Burning Rate					
Intercept	871,725.6	1	871,725.6	130.5345	0.000000*
FRT	20,475.6	1	20,475.6	3.0661	0.089524
TM	16,686.9	3	5,562.3	0.8329	0.485707
FRT × TM	31,036.9	3	10,345.6	1.5492	0.220857
Error	213,700.0	32	6,678.1		

* Statistically significant ($P < 0.05$) factors or its combination

Weight Loss

The WL is a factor that directly represents the wood flammability, *i.e.* the greater the WL of the wood, then the higher its flammability. A statistical evaluation of the effect of the TM on the WL is shown in Fig. 4. On average, the WL of the thermally unmodified wood was 7.5%. The thermally modified wood exhibited the highest WL of 11.6% at the lowest temperature of 160 °C, and the WL gradually decreased as the temperature increased. The wood thermally modified at 210 °C had a WL identical to that of the unmodified wood.

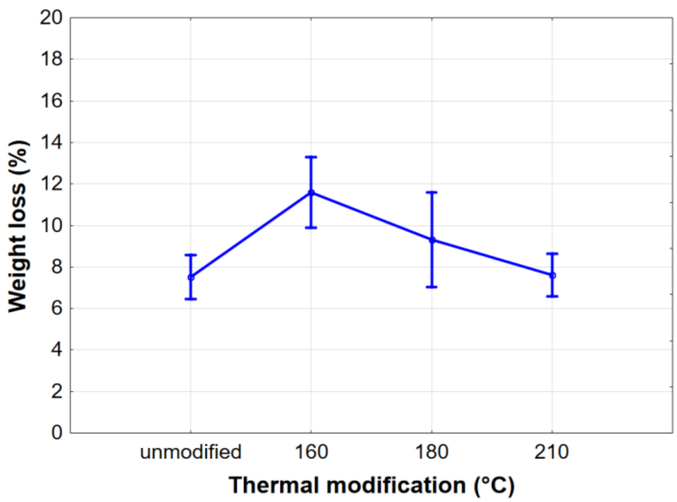

Fig. 4. Effect of the TM on the WL

The effect of the fire retardant (Fig. 5) was significant, and as was expected, the WL was lower for the wood with the fire retardant coating. The fire retardant reduces the burning capacity of wood, which logically suggests that the WL of the wood should be lower. The wood without the FRT had an average WL of 13.2%, while the wood with the FRT had a WL of only 4.8%, which was a decrease of 63.6%.

Fig. 5. Effect of the FRT on the WL

The interaction between the FRT and TM is shown in Fig. 6. The wood without the FRT showed more pronounced differences in the WL values found for the treated wood. The highest WL values for the wood without the FRT were found for the wood modified at 160 and 180 °C. In this case, it is interesting to note that the average WL of the unmodified wood was 9.9%, and for the wood thermally modified at 210 °C, it was 10.5%, which was a small difference.

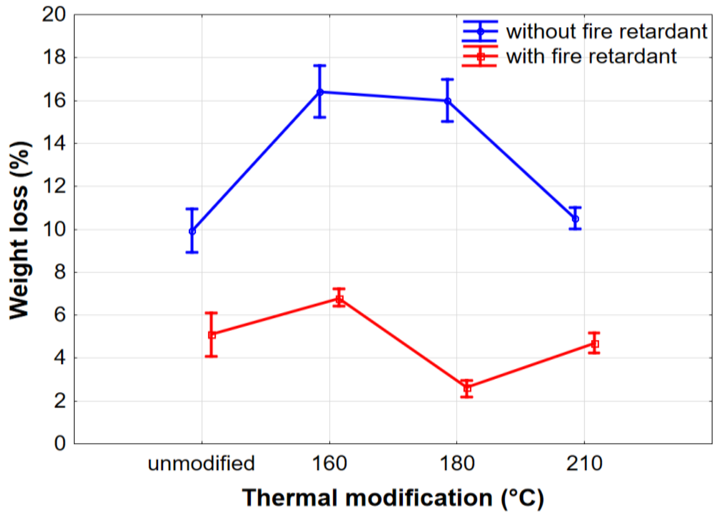

Fig. 6. Effect of the TM and FRT on the WL

In the case of the wood with the FRT, smaller differences were observed at the different TM temperatures. As with the previous case, the highest WL was measured at 160 °C, but the lowest WL was achieved with the wood thermally modified at 180 °C.

Burning Rate

The BR represents the spread of fire on a material over a certain time, *i.e*. a higher BR means a better flammability of the material. In this study, the effect of the TM on the BR was not clear (Fig. 7). The highest BR (13.2×10^{-5} %/s) was measured in the wood thermally modified at 180 °C.

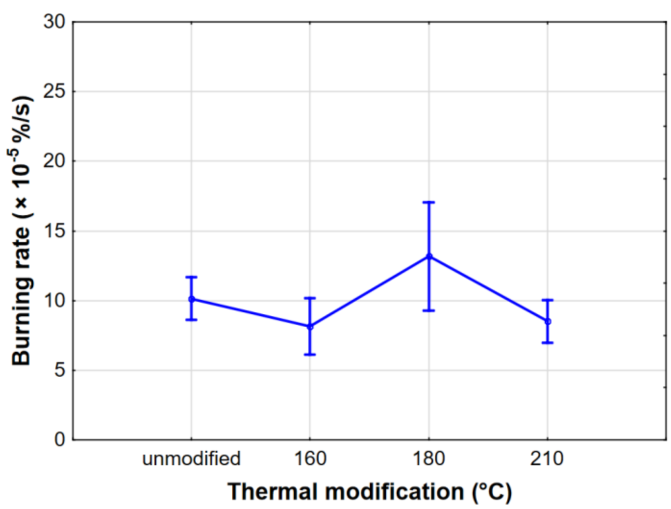

Fig. 7. Effect of the TM on the BR

In contrast, the unmodified wood achieved a 30.7% lower BR compared with the wood thermally modified at 180 °C. The BR values of the wood thermally modified at 160 and 210 °C were almost the same. Čekovská *et al*. (2017a), who investigated the effect of TM on the burning characteristics of spruce wood, found a similar effect from the modification temperature on the BR.

The FRT (Fig. 8) had the same effect on the BR as it did on the WL, *i.e*. the wood with the applied fire retardant had a lower BR (5.4 × 10^{-5} %/s) than that of the wood without the FRT (14.6 × 10^{-5} %/s). The BR decreased by 63% because of the fire retardant application. Fire retardants are specially designed to reduce burning, so this effect on the BR was expected. The previous works by Marney *et al*. (2008), Lowden and Hull (2013), and Jiang *et al*. (2014) confirmed this effect of fire retardants on various fire characteristics of wood.

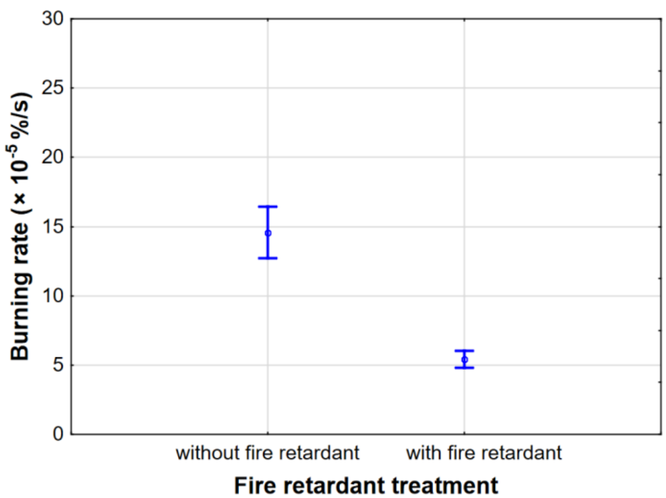

Fig. 8. Effect of the FRT on the BR

The thermally modified wood without the FRT exhibited great differences in the BR at individual TM temperatures (Fig. 9). The highest BR was found at 180 °C, while the lowest BR was found at 160 °C.

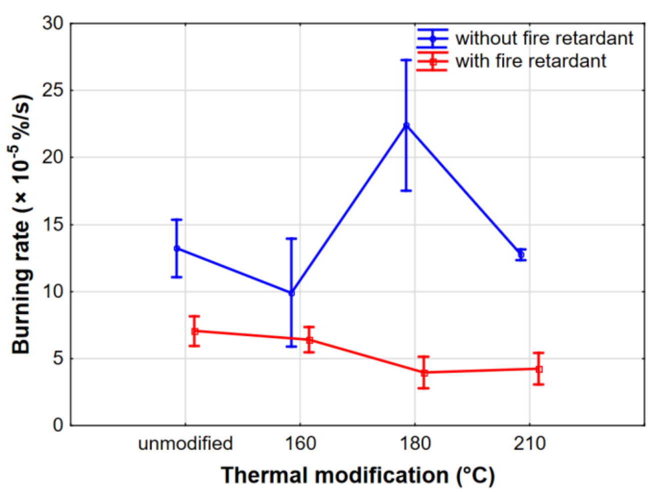

Fig. 9. Effect of the TM and FRT on the BR

The wood thermally modified at 210 °C achieved a BR similar to that found for the unmodified wood. The FRT had a clear effect on the BR. After the application of the FRT, these differences were reduced and the BR was dependent on the TM temperature, *i.e.* the BR decreased as the modification temperature rose.

Maximum Burning Rate

The dependence of the MBR on the TM temperature (Fig. 10) was very similar to that found for the BR. A significant difference was evident in the wood thermally modified at 160 °C, where the MBR values were the highest (44.3 × 10^{-5} %/s), which was the opposite of the trend seen for the BR (Fig. 7). The MBR value for the wood thermally modified at 180 °C was 9.5% higher than that of the wood thermally modified at 210 °C. The MBR value of the wood thermally modified at 210 °C was close to the value achieved for the unmodified wood, with a difference of only 1.7%.

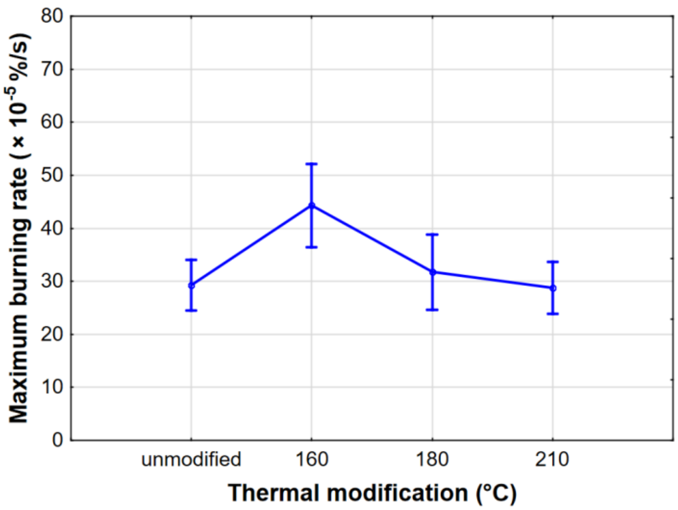

Fig. 10. Effect of the TM on the MBR

In the case of the MBR, the FRT (Fig. 11) also had a significant effect on its values. As for the previously discussed properties, the wood with the FRT achieved significantly lower MBR values.

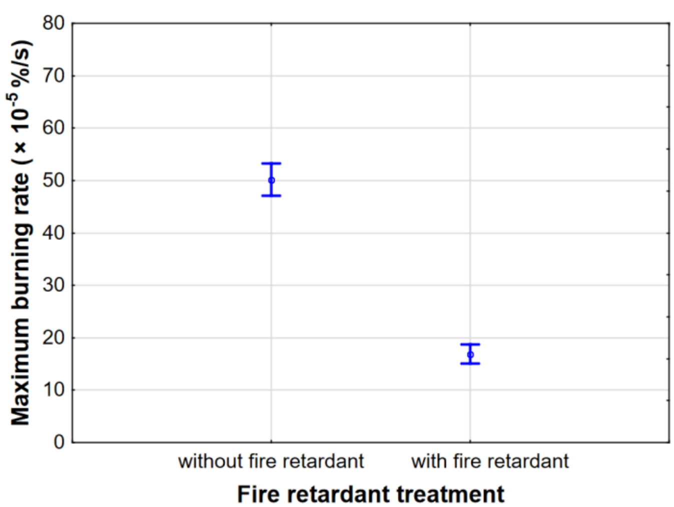

Fig. 11. Effect of the FRT on the MBR

The FRT reduced the MBR by 66.3%, which was similar to the decrease seen for the BR.

For the effects of the FRT and TM on the MBR (Fig. 12), there were differences compared with the BR. The wood without the FRT reached the highest MBR values at a TM temperature of 160 °C, which was the opposite of the trend observed for the BR (Fig.

9). For the wood with the FRT, the highest MBR value was achieved at a TM temperature of 160 °C, and the lowest value was achieved at 180 °C.

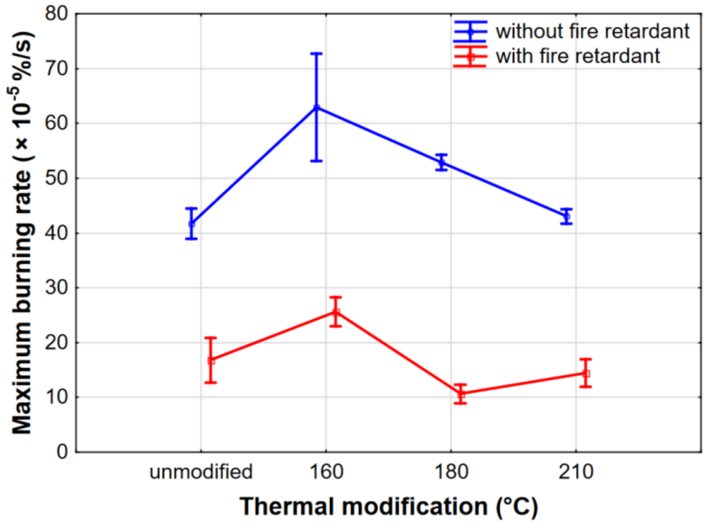

Fig. 12. Effect of the TM and FRT on the MBR

Time to Reach the Maximum Burning Rate

The TRMBR is a MBR-dependent factor, but has an opposite trend, *i.e*. the higher the TRMBR, the slower the material burns. The TRMBR was strongly affected by the TM temperature (Fig. 13). As the temperature increased, the TRMBR values gradually decreased. The only significant change occurred at a TM temperature of 160 °C, where the TRMBR was significantly lower (120 s) compared with the other temperatures.

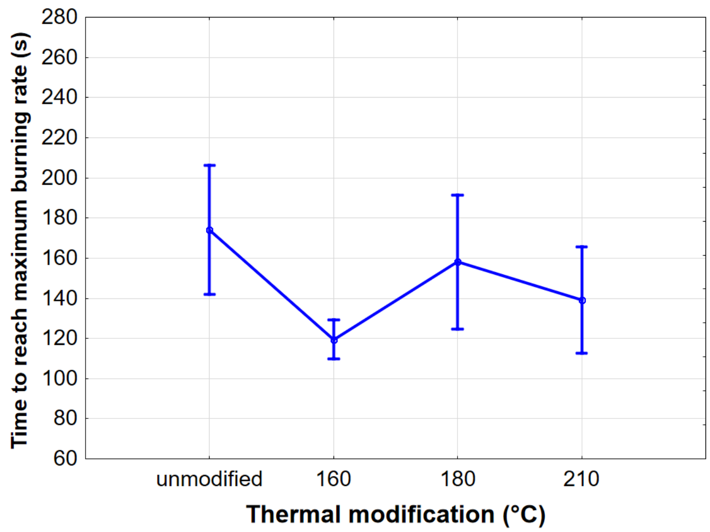

Fig. 13. Effect of the TM on the TRMBR

As was expected, the FRT had a strong effect on the TRMBR (Fig. 14). The higher the fire retardant ability, the higher the TRMBR. The wood treated with a fire retardant achieved TRMBR values that were 26.6% higher than that of the untreated wood.

Fig. 14. Effect of the FRT on the TRMBR

Generally, the TRMBR was dependent on both the TM temperature and FRT (Fig. 15 and Table 5). The application of a fire retardant caused the thermally modified wood to achieve higher TRMBR values as the temperature increased for almost all of the samples, except for the wood modified at 160 °C. In contrast, the wood without the FRT showed the exact opposite behavior, *i.e*. as the TM temperature increased, the TRMBR significantly decreased. The TRMBR for the wood without TM was 188 s, while the wood thermally modified at 210 °C only reached 86 s, which was a decrease of 54.3%. Čekovská *et al*. (2017a) found significantly smaller differences in the TRMBR values in relation to the increase in the TM temperature for spruce wood.

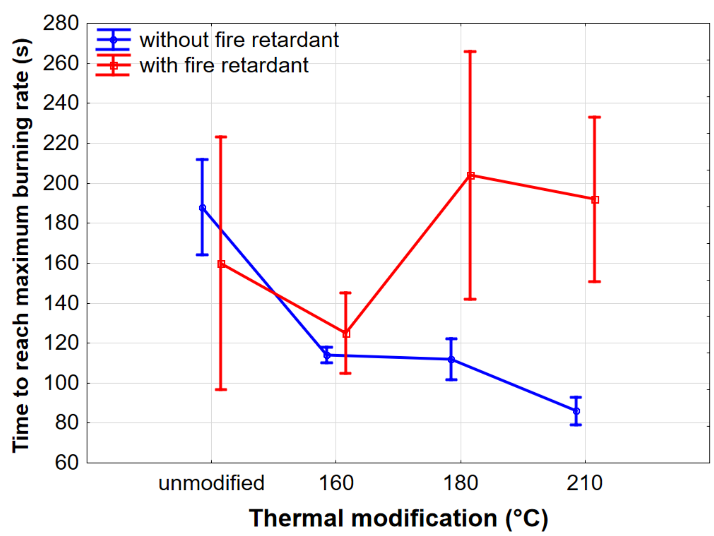

Fig. 15. Effect of the TM and FRT on the TRMBR

The results in Table 5 show that in some cases there was a higher weight loss, but the burning rate was the lowest. The relationship between BR and WL was not directly proportional. WL represents the total loss of weight relative to the original weight of sample, but does not describe how fast each proportion of wood was burnt over a 10-second measuring interval. BR is influenced not only by the amount of the burnt mass of wood, but also by the proportion of its basic constituents found there. Higher proportion of hemicelluloses mean faster burning, but lower weight loss. Conversely, a higher proportion of cellulose and lignin means slower burning, but higher weight loss. These proportions are also influenced by the thermal modification, which influences the various components differently. Hemicellulose is the least resistant to temperatures and its decomposition is up to 200 °C. Above this temperature, only cellulose and lignin remain, but they burn more slowly than hemicellulose.

Table 5. Average Values of the Flammability Characteristics

Factors		Flammability Characteristics			
Fire Retardant Treatment	**Thermal Modification** (°C)	**Weight Loss** (%)	**Burning Rate** (× 10^{-5} %/s)	**Maximum Burning Rate** (× 10^{-5} %/s)	**Time to Reach Maximum Burning Rate** (s)
without FRT	unmodified (reference)	9.9 (22.8)	13.2 (16.1)	41.7 (14.5)	188 (2.8)
without FRT	160	16.4 (16.3)	9.9 (14.8)	62.9 (3.5)	114 (7.8)
without FRT	180	16.0 (13.5)	22.4 (18.6)	52.9 (5.9)	112 (2.3)
without FRT	210	10.5 (10.7)	12.8 (6.9)	43.0 (1.5)	86 (17.6)
with FRT	unmodified (reference)	5.1 (4.4)	7.1 (3.5)	16.8 (5.4)	160 (8.8)
with FRT	160	6.8 (4.7)	6.4 (3.3)	25.7 (2.3)	125 (3.6)
with FRT	180	2.6 (20.4)	3.9 (6.7)	10.6 (3.6)	204 (6.8)
with FRT	210	4.7 (12.5)	4.3 (6.2)	14.4 (3.9)	192 (4.8)

The values in parentheses are the coefficients of variation (CV, %).

Thermally modified wood has properties that have been changed, which affect its ignition and subsequent burning behavior. The properties of thermally modified wood depend not only on the wood species and its properties, but also on the modification method and final temperature used during modification. Under high temperatures, the three basic components of wood begin gradually decompose, which produces volatile gases, tar, and carbonaceous char (Lowden and Hull 2013). However, each component has a different resistance. TM up to 210 °C (the highest temperature in this study) affects all of the basic wood components, but hemicellulose pyrolysis is the most pronounced process because it begins at 180 °C (Kim *et al*. 2006). High temperatures cause the degradation of cell wall polymers, which results in a reduction in volatile pyrolysis products and reduces the flammability of the wood (Hirata *et al*. 1991; Kol and Sefil 2011). From this perspective, thermally modified wood should be more suitable in regards to fire safety. In contrast, depending on the TM temperature, the surface integrity of the thermally modified wood is disrupted to a certain extent, which leads to easier ignition. The surface application of fire retardants is therefore suitable for thermally modified wood.

In general, wood treated with fire retardants requires a higher temperature and longer exposure to flames to burn. When the wood is exposed to flames, it releases pyrolysis gases, which, however, contains less combustible gases needed for the wood to burn (Hagen *et al*. 2009). Flame retardants based on phosphorus are the most common fireproof chemicals for wood (Schartel 2010). Their advantage is that they directly affect the thermal degradation of wood. During wood pyrolysis, the phosphorus components produce acids that reduce the decomposition temperature. This effect results in char formation and the dehydration of wood components (George and Susott 1971; Stevens *et al*. 2006). With this char layer on the surface, wood can resist further flame exposure because this layer increases the thermal resistance between the underlying wood and pyrolysis. The result is a reduction in the heat release rate and creation of a barrier against the release of volatiles from the wood and their subsequent mixing with oxygen in the air (Yang *et al*. 2003). Additionally, it is assumed that phosphorus prevents the formation of flammable components (*e.g*. tar = levoglucosan) by the phosphorylation of cellulose.

The information available on the flammability and burning of thermally modified wood with or without FRT is not extensive, and therefore it is important to study it further.

CONCLUSIONS

1. The WL did not have a clear dependence on the TM temperature, whereas the FRT had a clear effect. The highest WL values were found for the wood thermally modified at 160 and 180 °C, which were 16.4% and 16%, respectively. However, the WL observed in the wood thermally modified at 210 °C (9.9%) was comparable to the WL measured for the unmodified wood (10.5%). The differences in the wood with the FRT were much lower. As the TM temperature increased, the WL decreased, except for the wood modified at 160 °C.
2. The BR of the thermally modified wood without the FRT had different values depending on the TM temperature. The lowest BR was achieved at a TM temperature of 160 °C, and the highest BR was found for the wood modified at 180 °C. The BR of the wood modified at 210 °C was comparable to that of the unmodified wood. In contrast, the FRT application on the thermally modified wood resulted in the equalization of the differences and a gradual decrease in the BR of up to 38.1% as the modification temperature increased.
3. The MBR of the thermally modified wood with or without FRT had a similar dependence on the TM temperature, *i.e*. the highest MBR was found at a TM temperature of 160 °C. As the TM temperature increased further, the MBR decreased. The MBR values for the thermally modified wood ranged from 10.6 to 26.7 × 10^{-5} %/s, and for the thermally modified wood without the FRT, the MBR values ranged from 41.7 to 62.9 × 10^{-5} %/s.
4. The TRMBR of the thermally modified wood without the FRT decreased significantly as the TM temperature increased. The unmodified wood had an average TRMBR value of 188 s, but when the temperature was 160, 180, and 210 °C, it dropped to 114, 112, and 86 s, respectively. The FRT caused the TRMBR to increase to 192 and 204 s for the wood modified at 180 and 210 °C, respectively. For the modification at 160 °C, a decline in the TRMBR was observed.

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