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Heating Rate during Thermal Modification in Steam Atmosphere: Influence on the Properties of Maple and Ash Wood

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Abstract: This study aimed to compare two thermal modification (TM) schedules—with short and long heating phases—and their influence on the properties of maple (*Acer pseudoplatanus* L.) and ash (*Fraxinus excelsior* L.) wood. Two TM runs were conducted in industrial conditions (open system, steam atmosphere; substantially longer method compared to the processes usually described in the literature), with the same peak phase (200 °C, 3 h), but with different heating rates—slow (1.1 °C/h) and fast (2.5 °C/h). The results revealed that both TMs significantly reduced hygroscopicity and swelling of wood, but the influence of slow heating rate—through prolonged exposure of wood to relatively high temperatures—on dimensional stability was more pronounced. The modulus of elasticity, compressive strength and Brinell hardness remained mostly unchanged after TM (except for fast-modified maple), while the modulus of rupture was strongly reduced by TM in both species. It is assumed—at least in the case of maple wood—that a combination of initial moisture content above 8% and fast heating rate during TM can cause more intensive degradation of wood polymers. Relatively small differences in colour between slow- and fast-modified wood were found. The results confirmed the hypothesis that the heating phase is an important part of the TM schedule, and it can directly affect (together with peak temperature and time) certain wood properties.

Keywords: thermal modification; heating rate; maple; ash wood; wood properties

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1. Introduction

The industrial production of thermally modified (TM) wood began in the 1990s in Europe, and annual production gradually increased to currently more than 500,000 m^3 [1]. Thermal modification changes the properties of wood, mainly due hemicellulose degradation—it interferes with the load-sharing capabilities of the cell wall to decrease the strength and toughness of the wood, reduces the number of sorption sites for water and removes easily accessible nutrients for decay fungi [2]. The properties and characteristics of TM wood vary greatly, depending on the raw materials used [3], production methods (open/closed system; different treatment atmosphere) and conditions applied (treatment temperature and duration). Explaining the behaviour of TM wood as a time–temperature function was a topic of different studies [4–7], but due to numerous variables, a comparison of data reported in these studies is a difficult task. Most of the authors agreed that thermal degradation of the material modified under the same conditions is strongly dependent on the wood species and their chemical compositions [2,8]. On the other side, the same wood species behaves differently during modifications in different heat transfer media (steam, nitrogen, vacuum, oil, etc.) [1]. The variability of TM wood properties is even more pronounced on an industrial level due to uncontrolled variables [9] and dual coupling effects within boards and the stack [10]. Although there are some methods that can be used for quality control of TM wood, such as mass loss measurements [4,11], colour assessment [12,13] or spectroscopy techniques [14,15], one of the main difficulties remaining is to produce product with constant and controlled quality (durability, dimensional stability, colour).

Among all factors that influence the properties of TM wood, the most important are peak temperature and time [11], but the influence of heating rate (or time needed to reach the peak temperature) is less researched. In numerous papers, there is no information about the heating phase at all, or its potential influence is completely neglected when analysing the results. However, the heating time is considerably longer than the highest temperature period, and an important part of energy is exchanged during the heating phase. This is particularly pronounced at the industrial level, where this time is often significantly longer—especially with certain production methods—compared to laboratory experiments. When wood is heated for a prolonged time (48 h), degradation of hemicelluloses has been observed already at temperatures as low as 100 °C [16]. Torniainen et al. [9] reported darker colour of thicker boards modified at the industrial scale due to some degree of thermal degradation during longer heat-up times. It is well known that complex heat and mass transfer is occurring in wood, both during the heating and peak temperature phases of thermal modification. For example, the double pressure peak due to water evaporation and volatiles production—but also potential temperature overshoot—must be taken into consideration when modelling the process [17]. Some authors [18] suggested that moisture content in wood remains almost unchanged during the heating period (with a fast temperature rise), while the temperature on the wood surface is considerably higher than in its central part. Consequently, different temperature gradients can also be expected with different heating rates. Candelier et al. [19] found a high correlation between the kinetics of temperature used during the thermal modification process (representing the quantity of the effective heat power exchanged during the process) and mass loss (as a good indicator of the properties of TM wood). The relative area of temperature kinetics was usually calculated from the temperature profile versus time (expressed in °C·h) within the limits of a reference temperature (defined as the highest temperature at which mass loss does not occur): Borrega and Kärenlampi [20] chose 120 °C, Candelier et al. [19] 105 °C, while Allegretti et al. [5] used 132 °C. According to these values of a reference temperature, the heating rate (at least above 130 °C) also influences TM wood properties.

This study aimed to compare two thermal modification schedules—with short and long heating phases—and their influence on the properties of maple and ash wood. These species are among the few TM hardwoods for which there is a demand on the European market—the company where the research was carried out produces only TM maple and ash wood. Both schedules are prescribed by the equipment manufacturer, but it should be noted that even a schedule with short heating phases is longer than the processes that usually can be found in the literature [21]. Therefore, it was expected that the different durations of heating between schedules (in this case the difference was 2 days) has a more significant effect on the wood than in other production methods where the heating period is shorter. In addition, it was expected that a shorter schedule would bring organisational flexibility and lowered energy consumption, while a longer schedule could result in better dimensional stability of the products.

2. Materials and Methods

The research was carried out on kiln-dried, defect-free maple (*Acer pseudoplatanus* L.) and ash (*Fraxinus excelsior* L.) timber. After drying, the boards of both species were approximately 28 mm thick, 120 mm wide and 2.4 m long. Fourteen boards per species were selected and halves of the boards (Figure 1) were thermally modified in an industrial chamber (with the rest of 20 m^3 maple/ash batch), in a superheated steam atmosphere (open system) reached by water spraying (high- and low-pressure nozzles).

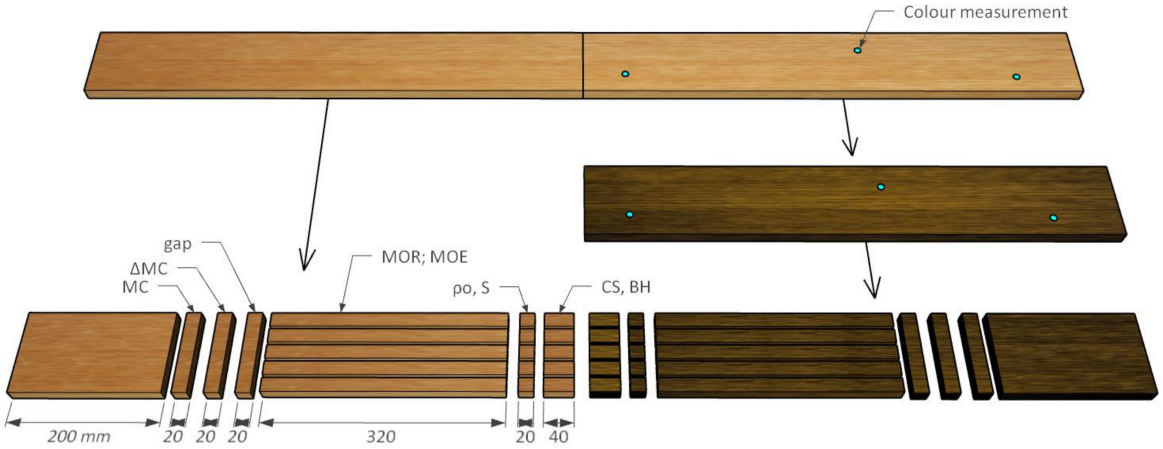


Figure 1. Sampling of unmodified and modified boards.

Two thermal modification cycles were conducted. The first 7 boards of each species were modified under a common industrial schedule ("Slow") that lasted 143 h, while the other 14 boards (7 of ash and 7 of maple) were treated under an alternative schedule ("Fast") in which the heating phases (temperature rise from 105 °C to 200 °C) were shortened for 47 h (Figure 2). The heating times during the slow and fast processes were 112 h and 65 h, respectively, while the average heating rates were 1.1 °C/h and 2.5 °C/h, respectively. The phase of the maximum temperature (200 °C, 3 h), as well as the conditioning and cooling phases (28 h), remained unchanged [22]. In this way, the total duration of the Fast modification was reduced to 96 h (2 days shorter than the Slow schedule).

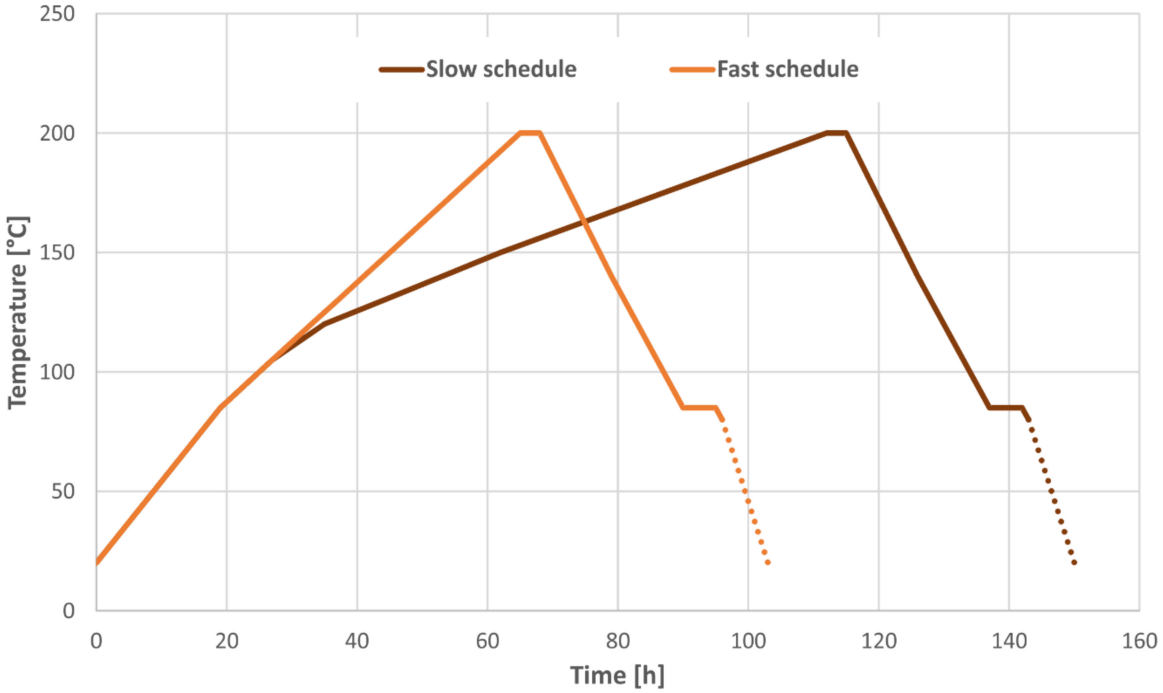


Figure 2. Phases of Slow and Fast thermal modification schedules.

All of the examined properties were determined both on unmodified and TM wood (Figure 1). The moisture content (MC) and MC profile across thickness were determined with the oven-dry method on specimens with full thickness and width of the board, while specimens of 20 × 20 × 20 mm^3 were used for density calculations.

The maximum swelling (S) was determined from oven-dried (103 °C, 30 h) modified and unmodified wood specimens with dimensions of 20 × 20 × 20 mm^3. The dimensions

were measured in the oven-dried state and the water-saturated state (average MC of maple specimens after water soaking: unmodified 127%, modified (slow) 102%, modified (fast) 105%; ash specimens: unmodified 100%, modified (slow) 74%, modified (fast) 71%). The volume swelling was calculated according to Equation (1):

$$S = \frac{V_{wet} - V_0}{V_0} \cdot 100\ (\%) \quad (1)$$

where V_{wet} is the volume in the wet (water-saturated) state (mm^3), and V_0 is the volume in the oven-dried state (mm^3). The equivalent equations were used for determination of tangential (T) and radial (R) swelling. In order to better predict wood behaviour in service, the swelling anisotropy ratio (T/R ratio) was calculated.

The anti-swelling efficiency (ASE) was determined to quantify the effect of different heating phases on dimensional stability:

$$ASE = \frac{S_u - S_m}{S_u} \cdot 100\ (\%) \quad (2)$$

where S_u is the volume swelling of water-saturated unmodified wood (%), S_m is the volume swelling of water-saturated TM wood (%).

Afterwards, 56 new maple and 56 new ash wood specimens (14 from slow-modified boards, 14 fast-modified, 28 unmodified) with dimensions of 20 × 20 × 40 mm^3 were made for sorption examinations. The specimens were first climatised in room conditions (20 ± 2 °C/44 ± 8%) for 12 months. Then, they were placed in a climate chamber (Kambič KK-105 CH) in conditions of 20 °C/72% until a constant mass was reached, and then in conditions of 20 °C/85% to determine the EMC at two different RHs. Half of all specimens were oven-dried prior to placement in the climate chamber, while the other half began from EMC reached in room conditions.

The three-point bending test (specimens 20 × 20 × 320 mm^3, 280 mm between supports) was used to determine the modulus of elasticity (MOE) and modulus of rupture (MOR) according to ISO 13061-4:2014 [23] and ISO 13061-3:2014 [24], respectively. Compressive strength (CS) was determined parallel to the grain according to ISO 13061-17:2019 [25], while Brinell hardness (BH) measurements (adopted EN 1534 [26], 500 N load) were carried out both on the radial and tangential surface. The colour was measured at 3 spots on planed surfaces (colourimeter EasyCo 566, Erichsen; 10° standard observer, D65 standard illuminant).

One-way ANOVA was used to determine statistically significant differences between groups' mean values (unmodified, slow- and fast-modified samples), while Tukey's test was used for post hoc analysis.

3. Results and Discussion

3.1. Hygroscopicity and Dimensional Stability

The MC of maple timber after conventional drying was 7.6%, and lower values were found after thermal modification (Table 1). A lower MC after slow TM compared to fast can be explained by prolonged exposure of wood to high temperatures during slow treatment. It can be assumed that 47 h longer exposure to high temperatures (when raised from 105 °C to 200 °C) during slow treatment caused higher degradation of wood. Even with the highest "reference temperature" being used (Allegretti et al. [5], 132 °C), it is clear that a significant part of effective heat power was exchanged during heating phases, i.e., the duration of these phases also affected the properties of TM wood. This is true even when taking into account the nonlinear influence of temperature and time in the relative area calculation [5].

Table 1. Moisture content of unmodified and thermally modified maple and ash wood, after treatment and after 12 months in room conditions (20 ± 2 °C/44 ± 8%).

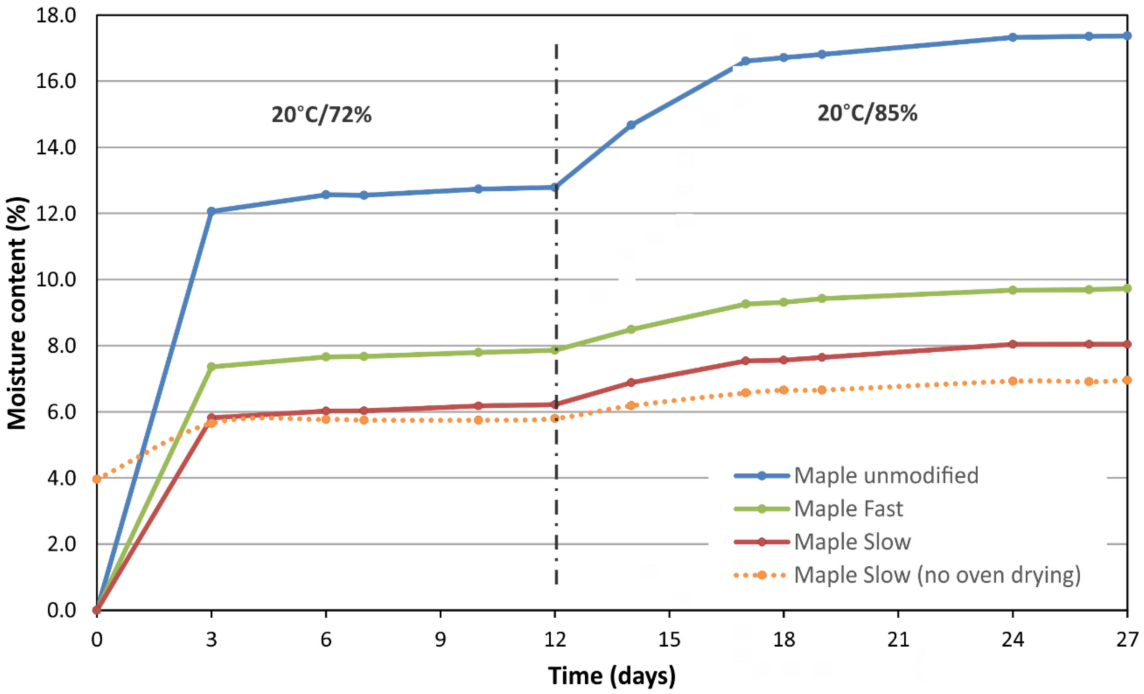
	MC [%]		MC [%] after 12 Months in Room Conditions	
	Maple	**Ash**	**Maple**	**Ash**
Unmodified	7.6 (0.3) *	5.8 (0.9) *	8.2 (0.2)	8.1 (0.2)
Slow TM	4.0 (0.3)	3.5 [b] (0.4)	4.0 (0.3)	3.9 (0.3)
Fast TM	5.4 (0.5)	4.1 [b] (0.3)	5.3 (0.3)	4.5 (0.2)

* After kiln-drying; standard deviation in brackets; letter b indicates no significant difference between treatments for ash wood after treatment.

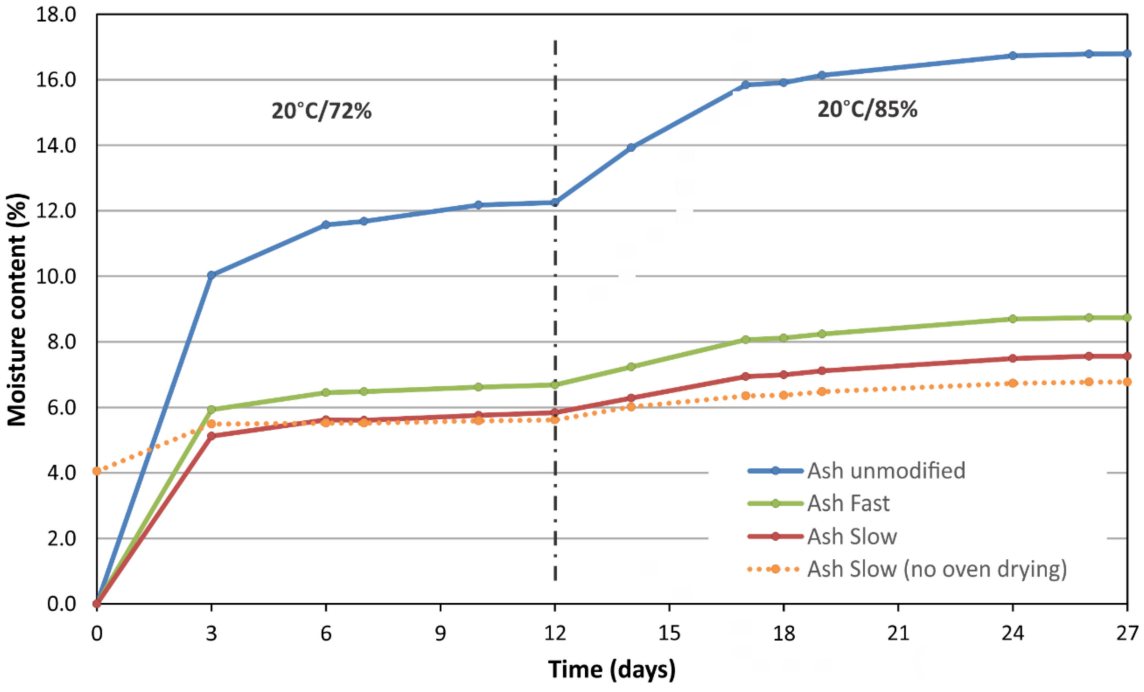
Although the influence of different temperature kinetics can be clearly seen on the MC of maple boards, there is no statistical confirmation of that influence for ash boards when measured immediately after the modification (Table 1). Potential causes for this could be a lower initial MC (5.8%) and different chemical changes in ash wood during the TM process. However, the lower MC of ash compared to maple boards, both after slow and fast modification, implies that ash wood needs more time to "return" moisture (and reach the appropriate EMC; the same trend of slower adsorption for ash specimens can be seen in Figure 3). This is confirmed by measurements after 12 months in room conditions (Table 1): the MC of ash specimens was higher by 0.4% for both treatments, while the MC of maple specimens remained unchanged.

The MC achieved after 12 months in room conditions reveals that slow modification results in lower EMC values (Table 1). For both species, there was a statistically significant difference in MC between treatments, and this difference was greater in maple than in ash wood. The MC of unmodified specimens was about 8%, while the MC of the slow-modified wood was approximately half as much; somewhat higher MC values were recorded for fast-modified wood. The observed EMC ratio of modified related to unmodified wood (MC_{mod}/MC_{unmod}) was between 0.48 (both maple and ash, slow treatment) and 0.65 (maple, fast treatment).

The existence of this difference in the hygroscopicity of wood modified by different treatments was also confirmed in controlled conditions, i.e., during climatisation in a climate chamber. It is clear that for both species, the slower schedule resulted in lower EMC values (Figure 3). This confirms the influence of the duration of the heating phases on the hygroscopicity of TM wood. Considering the nonlinear influence of temperature and time, in this experiment, the decisive difference was the last phase of heating—slow modification heating from 150 °C to 200 °C was 30 h longer as compared to a fast schedule. This is in line with Allegretti et al. [5], who reported a significant influence of heating time from 145 °C to 200 °C on the intensity of thermal degradation (with more intensive influence at higher temperatures). Here, the difference in EMC values between slow- and fast-modified wood was higher for maple than for ash wood. In general, the EMCs of all specimens (both unmodified and modified) were higher for maple than for ash (due to different chemical compositions), but the lowest reduction in hygroscopicity was found for fast modified maple wood (green line on Figure 3). The explanation for this higher EMC could be the combination of a higher initial MC of maple with the short heating period. This combination could potentially mean a presence of a small amount of water in the wood at the moment when the chemical transformation began, which decreased the effect on hygroscopicity. Rautkari and Hill [27] found that increasing the initial MC of Scots pine sapwood, in the range between 0 and 26%, decreased the effectiveness of the dimensional stabilisation and the reduction in EMC. Altgen et al. [28] reported that the modification in the oven-dried state increased the cell wall matrix stiffness, which improved the dimensional stability and hygroscopicity of wood. In this research, modification of oven-dried wood—and by that, enhanced condensation and cross-linking reaction—was guaranteed only in the case of slow treatment.



(**a**)



(**b**)

Figure 3. Sorption of Slow and Fast thermally modified wood at two RH values: (**a**) maple; (**b**) ash wood.

The dotted line in Figure 3 depicts the MC during climatising of specimens that were not oven-dried before the climate chamber. It can be seen that these specimens reached lower MC values than those for oven-dried wood—only slow-modified specimens were shown for both species, but the trend was the same for fast modification. This surprising phenomenon can probably be related to additional drying stresses that occurred in the amorphous cell wall during oven-drying of TM wood. These stresses were relaxed by

subsequent moistening of the wood [2], resulting in higher EMC values for oven-dried TM wood. Unmodified oven-dried wood reached the same EMC values as the unmodified specimens that began from room conditions.

The EMC ratio was lower for slow- than for fast-modified specimens, but also (for both treatments) lower at higher relative air humidity (Table 2). The latter is in line with the findings of Cai and Zhou [29] and García-Iruela et al. [30], and demonstrates the potential of TM wood to be even more dimensionally stable in moist conditions (but below 90% RH) than could be assumed by predictions based on the results obtained in room conditions. In general, the EMC reduction of slow-modified wood (up to 60%) was at the upper limit or even higher compared to the values reported for hardwoods modified at 200 °C [4,31,32].

Table 2. EMC ratios (MC_{mod}/MC_{unmod}) for slow and fast treatment at 20 °C and two RH values.

MC_{mod}/MC_{unmod}	Maple		Ash	
	RH = 72%	**RH = 85%**	**RH = 72%**	**RH = 85%**
Slow TM	0.45	0.40	0.45	0.40
Fast TM	0.59	0.50	0.51	0.45

It was shown that TM affected the oven-dry density and swelling (after capillary water uptake) of wood (Table 3). Both modifications reduced the oven-dry density in maple wood, while this is the case only for slow treatment in ash wood. At the same time, no significant differences were found between oven-dry densities of slow- and fast-modified specimens (neither for maple nor for ash). On the other hand, for both species, there was a significant difference between the swelling of all three groups of specimens (the only exception was radial swelling between slow- and fast-modified maple wood, where the difference was not confirmed due to relatively high variations in radial swelling in fast-treated wood). The slow modification clearly reduced swelling (both for volume and cross-section values) more than the fast process did. It can be assumed that more exchanged heat during slow modification probably led to a more intensive formation of aggregated structures [1], a greater increase in the cell wall stiffness and restriction of the nanopores expansion [33]. The ratio of tangential-to-radial swelling (swelling anisotropy ratio, T/R) for the unmodified maple specimens was 2.18; for slow TM wood it was reduced to 1.94, but remained unchanged (2.17) for fast modification. For unmodified ash specimens, the T/R ratio was 2.36, while for TM wood it was reduced to 1.89 for slow- and 1.84 for fast-modified wood. This is in line with the results of Sargent [34], who reported a significant decrease in the T/R for TM specimens compared to unmodified wood. Čermak et al. [35] and Bak and Németh [36] also reported a reduction in the T/R for hardwoods modified at 200 °C.

Table 3. Oven-dry density and swelling of unmodified and TM maple and ash wood.

		ρ_0 [kg/m^3]	Swelling (%)		
			Radial	**Tang.**	**Vol.**
Maple	**Unmodified**	583 (24)	4.21 (0.46)	9.19 (0.80)	14.21 (0.81)
	Slow TM	556 ^{a} (28)	2.39 ^{a} (0.20)	4.63 (0.41)	7.40 (0.57)
	Fast TM	539 ^{a} (39)	2.63 ^{a} (0.58)	5.71 (0.59)	8.78 (0.71)
Ash	**Unmodified**	679 (24)	5.72 (0.65)	13.49 (0.80)	20.40 (1.32)
	Slow TM	631 ^{b} (25)	2.69 (0.37)	5.10 (0.70)	8.27 (0.79)
	Fast TM	650 ^{b,*} (39)	3.23 (0.28)	5.94 (0.53)	9.56 (0.83)

Standard deviation in brackets; * indicates no significant difference compared to unmodified wood (Tukey's test, $p \leq 0.05$); equal letters (a for maple, b for ash) indicate no significant difference between treatments.

As a consequence of swelling reduction, the dimensional stability of TM wood—expressed as average ASE (Table 4)—was considerably improved. These improvements were attributed to the reduced amount of hydroxyl groups in hemicelluloses, cellulose

aggregation, cross-linking in lignin [1,37], and the presence of degradation products of the thermal modification, which may fill the wood micropores [1,4]. The mentioned changes are more pronounced during slow modification, due to prolonged exposure of wood to temperatures above 160 °C.

Table 4. Average anti-swelling efficiency (ASE) of thermally treated maple and ash wood.

ASE [%]	Maple	Ash
Slow TM	47.9	59.3
Fast TM	38.6	53.2

Although the obtained ASE values are within expected limits for hardwoods, dimensional stability was even more improved in ash specimens. In addition to its different chemical composition, ash is a species with higher density and conductivity (and lower diffusivity), and it can be expected that it is more sensitive to thermal degradation during TM [5,8]. Výbohová et al. [38] reported that the relative content of extractives in ash wood increased from 3.8% (control) to 6.9% after TM at 200 °C. Considering its better dimensional stability (higher ASE) and lower hygroscopicity (lower EMC), it can be expected that TM ash wood will perform better during use than TM maple. The same conclusion applies to slow versus fast modification—products made from slow-modified wood will perform better, concerning wood–water issues.

Overall, lower EMC (as an indicator of improved dimensional stability) and lower swelling after capillary water uptake guarantee better dimensional stability of TM wood for both species, and this especially applies to slow-modified wood. For practice, it may be important that the expected swelling rate of TM wood is also decreased [4].

3.2. Mechanical Properties

For both species, the MOE was less affected by TM compared to MOR (Table 5), which is in agreement with previous studies on hardwoods [13,39–42]. The MOE was significantly reduced (35%) only in fast-modified maple wood. A potential explanation for this is that with faster heating, a small amount of water remained in the wood at the moment when the chemical transformation began [43], which catalysed the chain splitting by acidic hydrolysis and promoted the degradation of wood polymers (lower oven-dry density, MOR and CS were also found in fast-modified maple specimens). In fast-modified ash wood, the MOE was significantly lower than in the slow-modified specimens. However, due to high variation, the difference in comparison to unmodified specimens was not statistically confirmed. Compared to the average value of unmodified specimens, the MORs were 23% and 35% lower for slow- and fast-modified maple wood, respectively. In the case of ash wood, the MOR reduction was even higher for slow-modified wood (37%). Again, high variation was noticed in fast-modified ash wood. It is confirmed that heating rate and species affect the properties of TM wood.

Table 5. Mechanical properties of unmodified and thermally modified maple and ash wood.

		MOE [N/mm^2]	MOR (N/mm^2)	CS (N/mm^2)	BH (N/mm^2)	
					Radial	Tangential
Maple	**Unmodified**	10,993 (1071)	128.8 (16.5)	74.4 (5.8)	29.1 (3.6)	35.2 (4.0)
	Slow TM	10,267 * (1012)	99.6 (17.5)	75.2 * (8.1)	27.5 * (4.1)	33.8 * (5.7)
	Fast TM	9101 (1272)	83.8 (19.1)	66.6 (7.7)	21.7 (4.2)	23.0 (5.4)
Ash	**Unmodified**	11,040 (1752)	131.8 (18.7)	78.6 (9.4)	34.8 (4.3)	41.8 (9.3)
	Slow TM	11,305 * (1281)	82.6 ^{b} (20.1)	81.2 ^{*,b} (9.4)	31.7 ^{*,b} (4.5)	31.1 (6.0)
	Fast TM	9514 * (1932)	91.0 ^{b} (27.9)	79.7 ^{*,b} (9.0)	35.3 ^{*,b} (6.0)	40.6 * (10.5)

Standard deviation in brackets; * indicates no significant difference compared to unmodified wood (Tukey's test, $p \leq 0.05$); equal letters (b for ash) indicate no significant difference between treatments.

The CS parallel to the grain was significantly reduced by TM only in the case of fast-modified maple, while in other groups this remained unchanged. Roszyk et al. [44]

reported similar CS values for untreated ash wood, but a significant reduction for ash modified at 200 °C. On the other hand, some authors [39,45], reported a slight increase in CS in TM ash wood, while in a few studies on TM hardwoods [46–48], CS remained unchanged. As in the case of the MOE/MOR and CS, a combination of somewhat higher initial MC and fast heating resulted in a reduction in the BH of maple wood, both in radial and tangential directions. No significant differences were found between other groups, with the exception of the BH in the tangential direction for slow-modified ash wood. The measurements on ash wood in the tangential direction were often influenced by its more porous structure and early/late wood differences, thus the obtained BH results are less reliable. The hardness values published for TM wood are often contradictory—both higher and lower results compared to unmodified wood can be found in the literature—and depend on the species, type of TM used, test method and test directions. In other studies on hardwoods [42,43,49], no or small BH reductions in TM wood were commonly reported. It can be assumed that with a low initial MC of wood, the duration of the heating phase has no influence on the CS and BH. However, with an initial MC higher than 8% (which is the common situation in the industry), a reduction in these mechanical properties can be expected when fast heating is conducted.

3.3. Colour

The visual inspection of maple and ash timber after both TM processes showed good quality (low numbers of cracks and deformations). As expected, modifications caused a much darker (lower L*) colour of wood (Table 6), also redder (higher a*), and in the case of maple more yellow (higher b*) [50,51]. However, as can be seen in Figure 4, the wood colour after two different treatments was similar (ΔE between thermal treatments was 5.1 for maple, and 4.9 for ash wood). No statistical difference between L* values after slow and fast treatment was found, while a* and b* values were somewhat higher after fast treatment in both species. It is known that the red component of wood colour is correlated with the content of extractives, while lignin derivates such as quinone and stilbenes generate the yellowing process during TM [52]. This study confirmed that a* and b* values in TM wood are both species- and process-dependent.

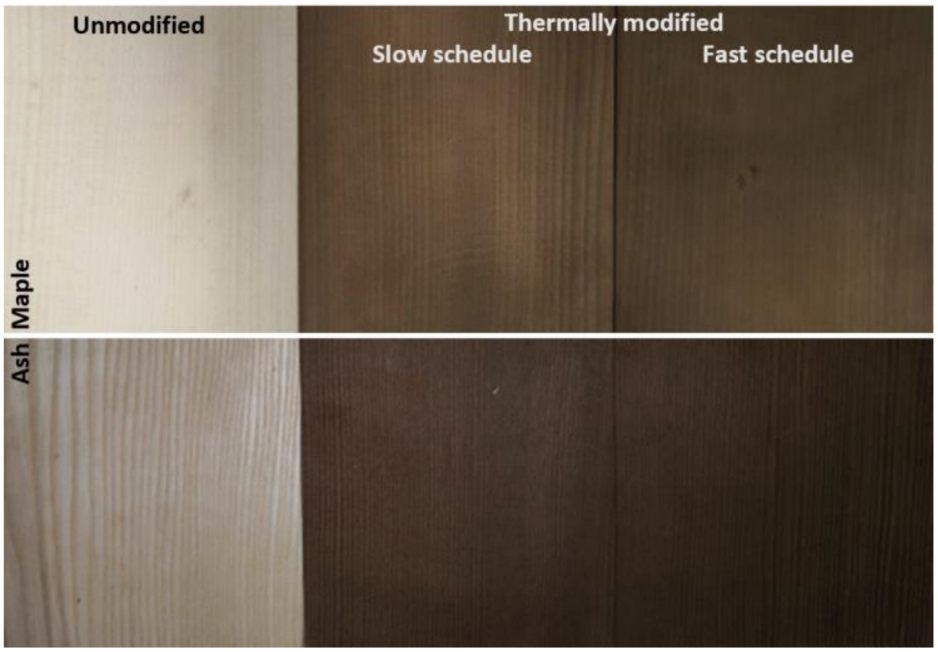


Figure 4. Unmodified and thermally modified maple and ash wood.

Table 6. Mean values of colour parameters of unmodified and thermally modified maple and ash wood.

		L *	a *	b *	ΔE * Un. vs. TM	ΔE * Slow vs. Fast
Maple	**Unmodified**	74.5 (2.8)	5.0 (0.8)	14.5 (0.9)	-	5.1
	Slow TM	44.1 [a] (2.2)	9.3 (0.3)	18.7 (1.7)	31.7 (3.8)	
	Fast TM	41.0 [a] (1.0)	10.8 (0.4)	22.4 (0.8)	34.5 (2.0)	
Ash	**Unmodified**	69.5 (3.1)	6.6 (1.0)	17.2 (1.6)	-	4.9
	Slow TM	39.6 [b] (1.4)	8.2 (0.3)	14.7 (1.2)	28.9 (3.9)	
	Fast TM	36.6 [b] (1.6)	10.1 (0.4)	18.2 * (0.8)	34.0 (3.4)	

Standard deviation in brackets; * indicates no significant difference compared to unmodified wood (Tukey's test, $p \leq 0.05$); equal letters (a for maple, b for ash) indicate no significant difference between treatments.

4. Conclusions

The focus of this research was on the heating phase during industrial TM, in which this phase typically lasts longer (65 or 112 h) as compared to common processes described in the literature. It was demonstrated that there is a substantial influence of the heating rate during thermal modification on the properties of the examined wood species. Both TMs—with slow (1.1 °C/h) and fast (2.5 °C/h) heating phases—significantly reduced hygroscopicity and swelling after capillary water uptake, and the effects were more pronounced in ash compared to maple wood. With the slow-heating TM, a better dimensional stability of wood was reached (both reduced EMC values and improved ASE). It is suggested that prolonged exposure to relatively high temperatures during slow heating reduces OH content, and enhances the cell wall stiffness and cross-linking reactions, which results in a reduction in hygroscopicity. The swelling anisotropy ratio was substantially reduced in TM ash wood, which can be significant for certain final products. The MOR values were strongly reduced by TM in both species (for 23%–37%), while the MOE, CS and BH remained mostly unchanged, except for fast-modified maple. In comparison to other TM groups, a decreased effect on dimensional stability (higher EMC ratio, lower ASE) and reduced mechanical properties were found in fast-modified maple. It is assumed that, due to the somewhat higher initial MC of maple and fast heating, a small amount of water remained in the wood at the moment when the chemical transformation began, causing more intensive degradation of wood polymers. Both modifications resulted in much darker and slightly redder colours compared to unmodified wood, while the colour difference between TM groups was relatively small (ΔE was 5.1 for maple and 4.9 for ash wood).

In summary, in comparison to fast TM, slower heating provided better dimensional stability (reduced EMC, higher ASE, lower T/R ratio) with similar mechanical properties (in maple even better), hence it can be recommended. This especially applies to situations when a higher initial MC of timber prior to TM is expected. Although the extended heating phase probably implies somewhat higher energy consumption, in many industrial TM processes, a gradual increase in temperature would enable a more precise realisation of the modification schedule, i.e., accurate parameters and uniform climate throughout the chamber. Our data provide further evidence that the properties of TM wood are both species- and process-dependent, and consequently the modification schedule must be adapted to the wood species and the desired properties of the product, especially taking into account the specifics of the production method itself. Finally, considering the significant influence of heating rate on wood properties, the need to provide data on the duration of the heating phase in TM-wood-related papers has been identified.

Although the results of the study support the conclusions drawn, examinations of chemical and anatomical changes in wood are necessary, in order to better explain the findings. In addition, durability tests on slow- and fast-modified wood will be conducted in the future to reveal how the heating rate during modification affects the biological resistance of TM wood.

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