Determining the Influence of Sample Thickness on the High-Temperature Drying of Beech Wood (*Fagus sylvatica* L.)

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Drying time reduction has always been a major concern in the drying process and is achievable by increasing the temperature of the surrounding air. To optimize the quality of the resulting material, drying conditions must be enhanced to reach a balanced correlation between the drying time and quality of the dried timber. This paper analyses the high-temperature drying of wood and the optimization of this process, as well as the effect that drying temperature and thickness of beech timber specimens has on the drying process. The high-temperature drying of beech wood was carried out by means of hot air in a laboratory drier for maximum 33 hours at maximum temperatures of 130 and 150 °C. The initial moisture content of samples was approximately 70%. The resulting drying times were short in comparison to conventional warm-air drying, which is caused by the high intensity of drying during the removal of bound water. Finally, it can be concluded that the thickness of the dried specimens is a significant factor in the process of high-temperature drying of beech wood

Key words: High-temperature drying; Moisture gradient; Temperature; Cross warping

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INTRODUCTION

Wood is the most frequently used material for interior and exterior structures because of its natural and aesthetic aspects and its simple processing. The drying of timber at temperatures above the boiling point of water is called high-temperature drying (Hillis 1984; Aydin and Colakoglu 2005). This technique has attracted considerable attention in recent years. The high-temperature drying of wood is an environmentally friendly method that is three to five times faster than warm-air drying (Trebula and Klement 2002). Drying wood at high temperatures (130 to 150 °C) is an effective method to improve the dimensional stability and biological durability of wood (Perré and Degiovanni 1990, 1999).

Based on the cited work, it is reasonable to expect that in the high temperature drying of beech the loss of moisture will be directly proportional to the drying time. When the temperature is raised above 100 °C, the drying time will be shortened, with a faster decrease of moisture content. According to Poncsák *et al.* (2006), the influence of temperature is more pronounced at higher moisture content. Drying times are short in comparison to conventional warm-air drying, which is attributable to the high intensity of drying during the removal of bound water (Klement and Marko 2009). Kollman (1952) reported that high-temperature drying requires 25 to 60% less energy than does normal kiln-drying. This reduction in energy is attributed primarily to better heat transfer to the wood and less heat loss through the kiln walls because drying time is shortened. The high temperature has a significant influence not only on the discoloration, but also on dimensional stability and mechanical properties of wood. However, the strength and especially toughness therewith is inevitable reduced (Okuyama *et al.* 1990). Burmester (1975) concludes that high-temperature drying of wood results in a large reduction in the hemicellulose content, and thus improves the dimensional stability of the wood. Drying fresh hardwoods species can cause some defects (warping, splits, color difference) (Bekhta and Niemz 2003). Also, the drying of wood from a moisture content of about 40 to 60% can lead to the occurrence of internal cracks (collapse) and external cracks too (Konopka *et al.* 2015). Drying temperature is the most important processing factor because it can be responsible for defects in each category (Klement and Huráková 2015). However, high-temperature drying of wood leads to visible changes in the timber, such as discoloration, and lower mechanical properties, such as shear strength (Sehlstedt-Persson 1995; Cividini *et al.* 2007). Wood color is a particularly important factor to account for when determining the price of wood. Subsequently, it is important to be familiar with the process of high-temperature drying and the identification of many factors affecting the properties of timber (Remond *et al.* 2007).

EXPERIMENTAL

Materials

Wood of beech (*Fagus sylvatica* L.) was used for experimental measurements. Samples were chosen from beech logs with diameter 40 cm and length 4 m. Beech logs were selected from forests of Technical University in Zvolen in October 2015. The content of the dry kiln consisted of 40 specimens. Test specimens with a thickness of approximately 25 and 32 mm, width of 120 mm, and length 350 mm were produced from two logs with diameters of 550 to 650 mm and lengths of three meters.

As illustrated in Fig. 1, the drying mode was divided into four parts. However, only in the third section was a different maximum temperature, of either 130 or 150 °C, used.

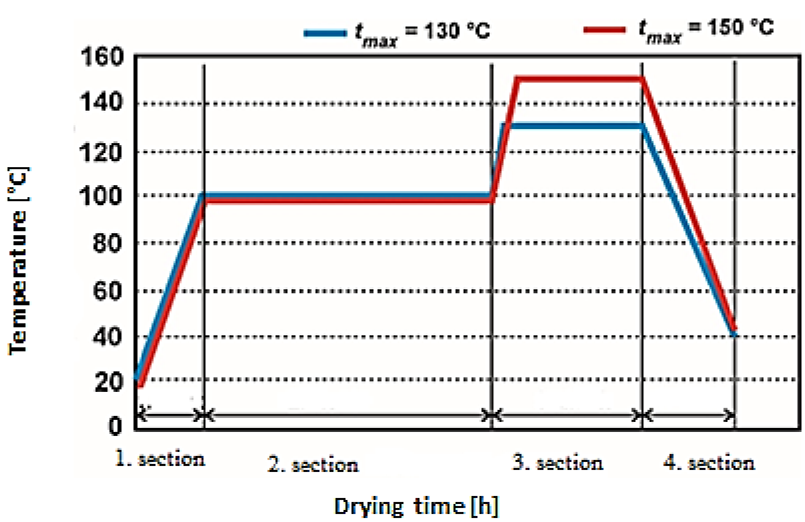

Fig. 1. Mode of high-temperature drying

In sections 1 and 2 of the process, the temperature of the surrounding air was maintained at the boiling point of water (100 °C) until the moisture content of the specimens did not fall below the fiber saturation point (sections 1 and 2). Then, the temperature was increased to the maximum value of either 130 or 150 °C (the third section). When a final moisture content of 8% to 10 % was achieved on the cross section of the material, the temperature was lowered to the temperature of the surrounding air (section 4). The rate of drying was 3±0.3 m s^{-1}.

Methods

The process of high-temperature drying was conducted in a laboratory kiln from BINDER company. Electrical spirals were used for heating. The moistening of the air was achieved by saturated steam. Drying parameters such as the temperature of dry and wet bulb and the temperature of the specimen with used Copper and Constantan thermocouples (Fig. 3) were investigated during the experiments. The overall scheme of the laboratory kiln is shown in Fig. 2.

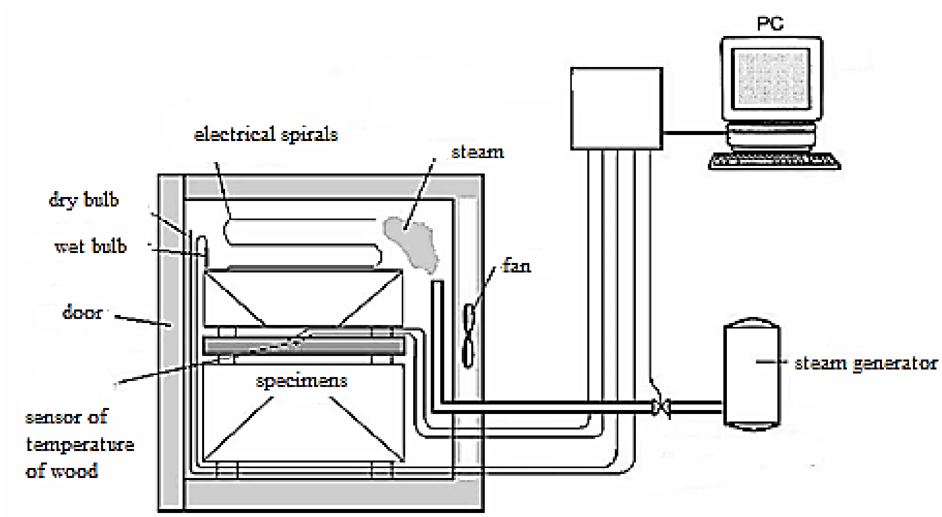

Fig. 2. Schematic of the laboratory kiln

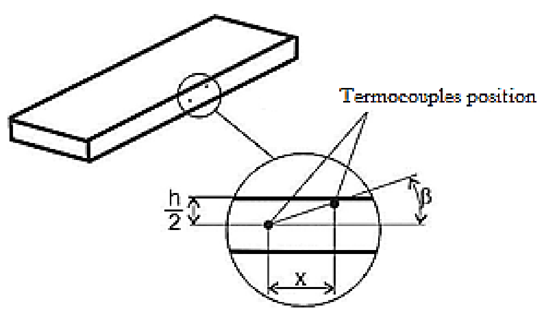

Fig. 3. Thermocouples position of in the specimen

Moisture and moisture gradients of the specimens (Fig. 4) were measured once every 3 h during the drying process. Simultaneously, the specimens were weighed and the current moisture was calculated. Cross warping and cracks were determined after the drying process.

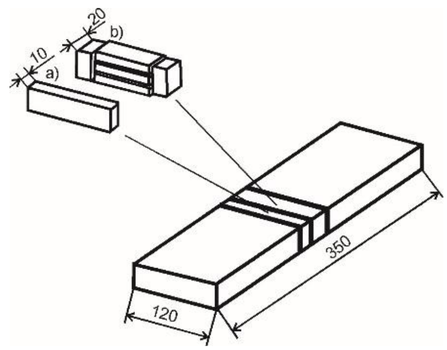

Fig. 4. Specimens for the detection of a) moisture and b) moisture gradient

Absolute moisture content of wood

The oven-dry method was used for the determination of moisture content. Weighing was performed with accuracy to the nearest 0.01 g. Drying to an absolute dry condition was performed in a laboratory kiln at 103 ± 2 °C. Moisture was calculated using Eq. 1,

$$w\ [\%] = \frac{m_{w-}\ m_0}{m_0} \cdot 100 \qquad (1)$$

where m_w is the weight of the moist specimen [g] and m_0 is the weight of the absolutely dry specimen [g].

Moisture gradient

Specimens for the determination of the moisture gradient were processed as illustrated in Fig. 5.

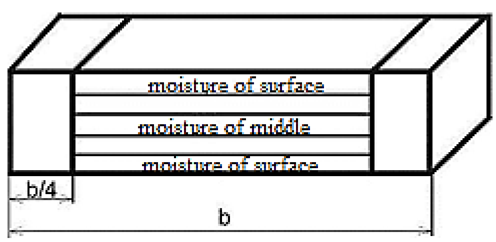

Fig. 5. The specimen of moisture gradient

The size of the moisture gradient was calculated using the equation,

$$\Delta w\ [\%] = m_m - m_s \qquad (2)$$

where m_m is the moisture of the middle layers [%] and m_s is the moisture of the surface layer [%].

Cross Warping

Cross warping was evaluated through relative warping. The values were calculated using Eq. 3,

$$K\ [\%] = \frac{f\ .100}{b} \qquad (3)$$

where f is the maximum curve [mm] and b is the width of lumber [mm].

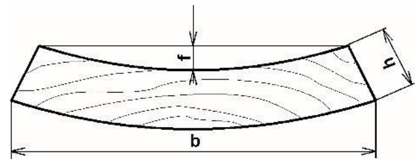

Fig. 6. The specimen of crosses warping

Cracks

Five specimens were randomly selected to evaluate cracks. The quantity, length, and width of cracks were determined at staggered distances of 25 mm from the face (Fig. 7). The measurement was carried out 10 times with using a magnifying glass.

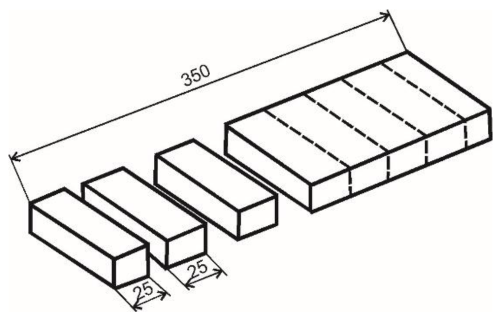

Fig. 7. Evaluation of cracks along the length of the specimens

RESULTS AND DISCUSSION

Table 1 shows the initial and final values of the moisture, drying time, average density, and the drying rate of specimens. When the thickness of the specimen was 25 mm, the drying rate was approximately 1.9%.h^{-1} at a temperature of 130 °C. At the drying temperature of 150 °C, the drying rate was 2.0%.h^{-1}. Similarly, when the thickness of the specimens was 32 mm, the drying rate was at a lower temperature of 130 ° C. Compared with the warm-air drying, the values are noticeable higher in the high-temperature drying.

Table 1. Summary Characteristics for Moisture Content of Wood, Drying Time, Drying Rate, and Drying Temperature at Various Thicknesses

Thickness of specimen (mm)	Temperature (°C)	Moisture (%)		Drying time (h)	Rate of drying (%.h^{-1})	Density ρ_0 (kg.m^{-3})
		Initial	Final			
25	130	69.1	12.6	30,0	1.9	702.0
	150	69.0	10.0	30.0	2.0	717.0
32	130	66.0	12.2	33.0	1.6	709.0
	150	69.6	9.4	33.0	1.8	695.0

Drying curves and the thicknesses of the drying temperature are shown in Fig. 8. In both thicknesses of the specimens and the drying temperature of 130 °C, the final moisture was higher than planned and achieved a value of 12% on average. The drying curves were linear, and therefore the loss of moisture was directly proportional to the drying time. Raising the drying temperature above 100 °C caused the acceleration of moisture loss. In this respect, the present observations are consistent with those of Poncsák *et al.* (2006). Compared with specimens of thickness 25 mm, the drying process of the 32-mm-thick specimens was longer, at approximately 3 h. As also shown by Klement and Marko (2009), drying times were short and the water removal process was more intensive in terms of bound water content when drying was carried out at high temperature.

Moisture gradients were measured at the beginning and end of drying. Figures 9 and 10 show the comparison of specimen moisture gradients with the same thickness but varied drying temperatures. The moisture gradients of all specimens were positive.

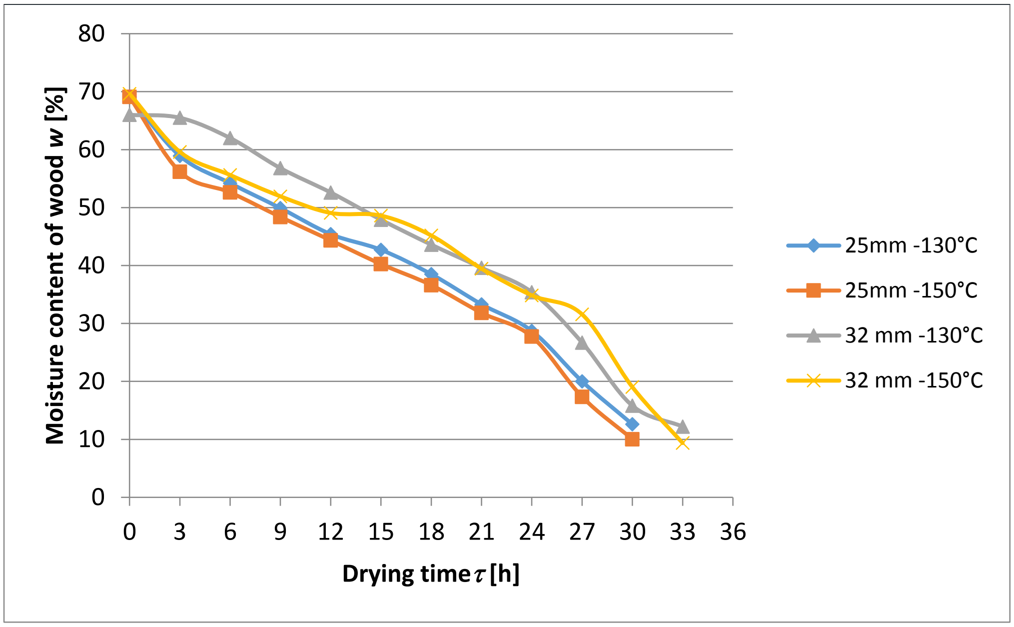

Fig. 8. Drying curves for each thickness and drying temperature

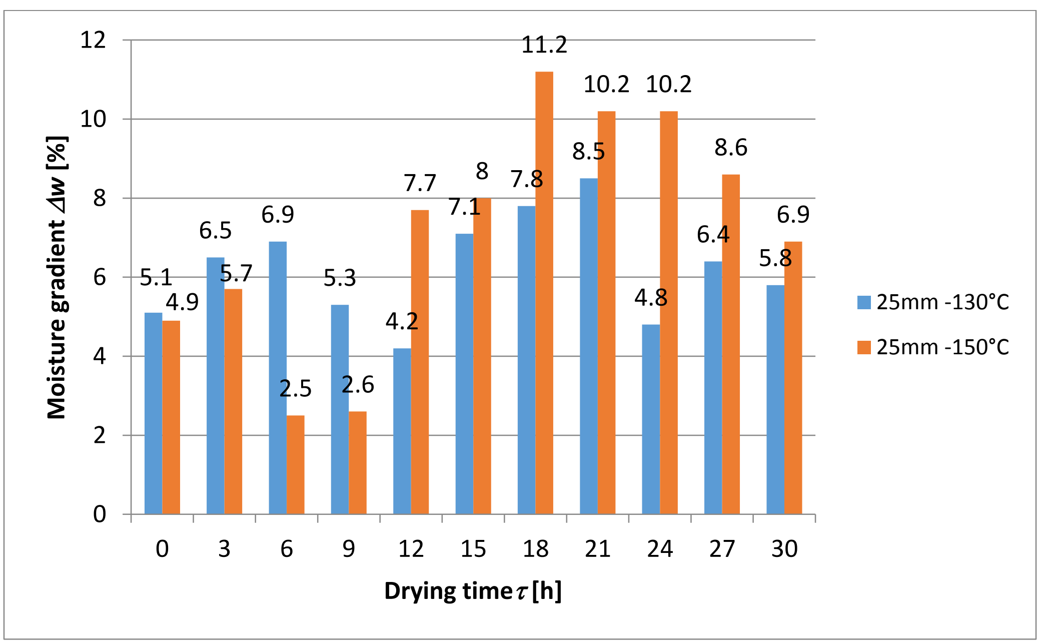

Fig. 9. Values of moisture gradients at various temperatures for 25 mm

When using the specimens with a thickness of 25 mm in the 100 °C section of drying, the moisture gradients were affected by the temperature of drying. The average moisture content of 30 % and drying temperature of 130 °C resulted in a moisture gradient of 7.8 %. However, at the drying temperature of 150 °C, the value of the moisture gradient was 11.2 %.

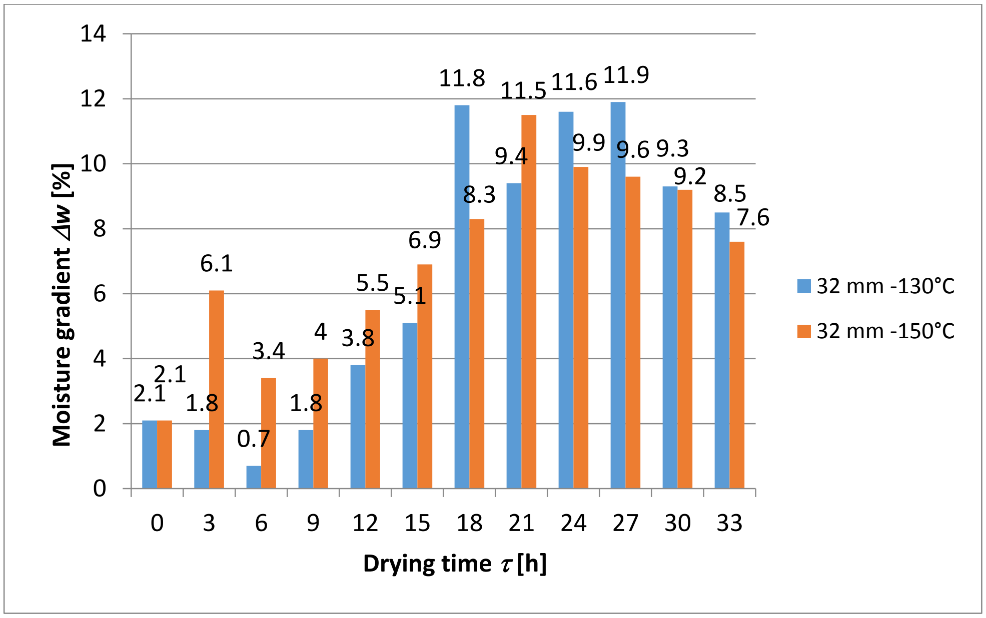

Fig. 10. Values of moisture gradients at various temperatures for 32 mm

When the thickness of the specimens was 32 mm, the measured values were very similar to the values measured using specimens with the thickness of 25 mm. The values of moisture gradients measured at both drying temperatures were higher when the 32 mm specimens were used.

At the end of drying, the moisture gradients at both drying temperatures were decreasing (Fig. 11); however, the final values were still large. The final stage of the drying process, based on the average moisture content of the wood, was not optimal.

The courses of the temperature of dry bulb (t_d) and wet bulb (t_w) during the drying process and temperature in the centre of the dried specimen and temperature on the surface of the dried specimen were dependent of the time and drying temperature of 130 °C of the specimens with the thickness of 25 mm. Courses of the dry bulb at the drying temperature of 150 °C and a thickness of 32 mm were similar.

The process of drying in terms of measured temperatures can be divided into sections. Firstly, the heating from the initial temperature to the temperature of the surrounding air was approximately 100 °C. The length of this section is approximately 2.5 h. The effect of the thickness of the specimens was not considered noticeable in terms of time. Throughout this section, the temperature of the surface of the timber specimen was higher than in the centre, whereas the difference was minimal.

The second section is characterized by the temperature of the surrounding air being kept at approximately 100 °C. The length of this section differs depending on the moisture and the thickness of the dried specimens. At a thickness of 25 mm, the time taken was 21 h. At the thickness of 32 mm it was 22 h. The temperatures of the specimens on the surface and in the middle were nearly identical, some differing only by approximately 1 °C.

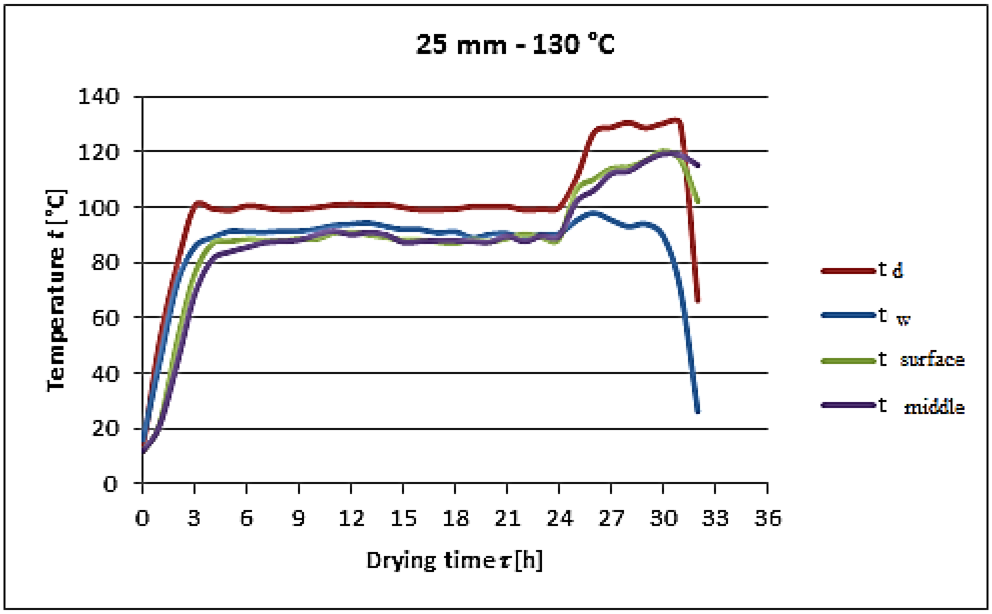

Fig. 11. Drying curves

At the beginning of the third section, the temperature of the surrounding air was increased from approximately 100 °C to the required temperature of 130 or 150 °C. Simultaneously, the temperature was kept until the desired final moisture content of the specimens was achieved. The wet bulb temperature was 100 °C.

The difference in the temperatures of the wood can be seen, whereas the temperature of the specimen on the surfaces was higher than the temperature in the middle. The thickness and the drying temperature affected the time variable of this section.

The cooling of wood was the last section of the drying process. It was a short section and its analysis is not considered noticeable. The value of the cross warping was measured on the selected specimens. The values were evaluated using two-way variance analysis. Thickness and the drying temperature affected the size of cross warping. The measured values of cross warping and its basic statistical characteristics are shown in Table 2 and the two-way variance analysis shown in Table 3.

Table 2. Cross Warping –Basic Statistical Characteristics

Thickness of specimen [mm]	Max temp. [°C]	Cross warping [mm]			Variance	Standard deviation	Fault	Coefficient	Number of specimens
		Average	Minimum	Maximum					
25	130	2.8	1.5	4.0	0.789	0.888	0.256	32.3	30
	150	2.3	1.1	3.9	0.918	0.958	0.277	41.3	30
32	130	2.3	0.9	3.5	0.776	0.881	0.254	38.0	30
	150	1.8	0.9	2.5	0.245	0.495	0.143	28.1	30

Perré (1990, 1999) regarded high temperature drying as a process that improves the dimensional stability of wood. The changes in the specimen shapes were small. The present work showed that average cross warping was between 1.8% and 2.8% (Table 3). Statistical analysis of the measured values showed that specimen thickness is an essential factor affecting the cross warping size (Table 3). The drying temperature was not considered statistically significant. The values of standard deviation were lower with a thickness of 32 mm than with a thickness of 25 mm. This means that the thickness had a positive effect on the cross warping size.

Table 3. Two-Way Analysis of Cross Warping

	Standard deviation	Degrees of freedom	Average quadrant	F-criteria	Level of Significance
Abs. member	291.85	1	291.85	418.6	0
Temperature	3.15	2	1.58	2.26	0.114
Thickness	4.42	1	4.42	6.344	0.015
Temperature-Thickness	0.12	2	0.06	0.089	0.915
Mistake/Fault	39.04	56	0.7	-	-

At a distance of 25 mm from the face, the occurrence of the front cracks in both thicknesses was frequent. The occurrence of cracks on the specimens with a thickness of 25 mm and a distance of 75 mm was rare. Cracks on the specimens with a thickness of 32 mm extended to a length of 125 mm. The plane of the cracks was radial, especially along the rays, whereas 12% to 25% of the cracks were wider than 20 mm, depending on the procedure used. Table 4 shows the results of the two-way variance analysis.

Table 4. Two-Way Analysis of Variance

	Standard deviation	Degree of freedom	Average quadrant	F-criteria	Level of significance
Abs. member	31994.19	1	31994.190	955.558	0.000
Temperature	324.09	2	162.040	4.840	0.008
Thickness	49.54	1	49.540	1.480	0.225
Temperature-Thickness	63.19	2	31.590	0.944	0.390
Mistake/Fault	10747.79	321	33.480		

The two-way analysis confirmed the statistically significant effect of temperature. A significant factor was the position of specimens in a stack. The specimens containing more cracks were situated on the periphery of the stack. Specimens placed in the lower part of the stack contained fewer cracks. However, some authors put forward observations that more significant factors for formation defects are the position within a log and the moisture content (Perré and Degiovanni 1990; Bekhta and Niemz 2003; Klement and Huráková 2015).

CONCLUSIONS

High temperature drying factors were scrutinised in this work relative to a theoretical analysis, which was verified by experimental work (Hillis 1984; Bekhta and Niemz 2003; Klement and Huráková 2015). As a consequence of high-temperature drying, the drying times were short in comparison to conventional warm-air drying, which can be attributed to the high intensity of drying during the removal of bound water. Results based on the drying times and the drying curves showed that the final drying time is affected by the thickness of the specimens.

On the basis of measured results of the two specimens of beech with various thickness and using maximum temperatures of 130 and 150 °C, the conclusions are summarized below:

1. The drying temperature can be regarded as a less significant factor relative to applying high-temperature drying during the preparation of beech-wood lumber.
2. The influence of drying temperature in terms of the thickness of the specimens was considered less significant. The effect of temperature on the size of the moisture gradient using the specimen with the thickness of 32 mm was not significant. The effect of the thickness on the maximum achieved values of moisture gradients was minimal, but on the final values of moisture gradient it was more significant.
3. The effect of specimen thickness on the cross warping size was statistically significant.
4. The adverse effects of high temperature drying on the appearance of front cracks could be seen. However, their number did not increase significantly because of the increase of temperature from 130 to 150 °C at both thicknesses.
5. Finally, it can be concluded that the thickness of the dried specimens is a significant factor in the process of high-temperature drying of beech wood at the maximum drying temperature. The drying temperature of 150 °C can be applied only for thicknesses of up to 25 mm. When the thicknesses are greater than 25 mm, the temperature has no significant effect on the length of drying time and has a negative impact on the quality of dried wood.

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