FOLIA FORESTALIA POLONICA

© *PAN* *Series B, Issue 38, 55-65, 2007*

EFFECTS OF EUROPEAN BEECH (*FAGUS SYLVATICA* L.) WOOD STEAMING ON SORPTION PROPERTIES AND KILN-DRYING INTENSITY

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SYNOPSIS. The sorption properties of unsteamed and steamed European beech wood were analyzed in order to determine the practical influence of the treatment on properties of the wood-water system. The Hailwood-Horrobin model was used to describe and explain changes in the equilibrium moisture content. The reduction of the dissolved water content was found after the treatment. The accessibility of water vapor to the sorption sites as well as the hydrated water content practically did not change. The kiln-drying intensity changes were also related to steaming. The recommendations for modifications of kiln-drying schedules considered the modified hygroscopic properties as well as the increase in the drying rate of steamed wood. The drying gradient values should be reduced during the initial stage of drying, i.e. for moisture content values above the Fiber Saturation Point, in order to obtain the demanded drying intensity and quality.

KEY WORDS: equilibrium moisture content, drying gradient, kiln-drying schedule

INTRODUCTION

The run of timber drying processes depends primary on a relation between drying air parameters and properties of the material to be dried. The relation influences the range of moisture content decrease as well as drying time. The instantaneous value of the ratio of the decrease and the time is usually called drying intensity. It was found by Harris et al. (1989) that the drying intensity of oak timber after steaming is higher as compared to unsteamed wood. The higher intensity was primary found in the initial phase of the drying process, i.e. for timber moisture contents higher than 30%. When the timber moisture content is lower than the Fiber Saturation Point (FSP) there were practically no observed differences in drying intensities of steamed and unsteamed timber.

The required drying intensity is set by the application of a proper drying schedule which relates air parameters to timber species, thickness, moisture content as well as drying quality. Drying schedules often use a concept of drying gradient (sometimes called as drying potential) to quantify the drying intensity. The drying gradient is defined as the ratio between the actual mean moisture content of timber and actual equilibrium moisture content in a dryer with the exception that for timber moisture contents above the FSP, the moisture content at the FSP has to be used instead of the actual moisture content. In spite of the reported higher drying intensities of steamed timber the drying schedules do not differ in their drying gradient values for unsteamed and steamed timber. It is well known that the application of too high drying gradients leads to unacceptable drying quality while the use of too low gradients causes the significant increase of drying time.

The literature reports dubious views on the importance of steaming on the change of sorption properties of wood. Unsal and Ayrilmis (2004) stated that the equilibrium moisture content changes after timber steaming are measurable but the differences should not be important from the practical point of view. Therefore, the objective of the present study was to determine changes in hygroscopic properties of beech timber after steaming as well as finding the influence of the properties on drying intensity. Additionally, the corrected values of the drying gradient will be proposed in order to take into account the modified hygroscopic properties and preserve the assumed drying quality.

MATERIAL AND METHODS

The investigations were made for European beech (*Fagus sylvatica* L.) wood. Flooring strips were obtained from the green material. The dimensions of the strips were 30 × 90 × 350 mm corresponding to radial, tangential and longitudinal directions, respectively. Immediately after the strips were obtained the rectangular prisms were cut from the central part of each strip (Fig. 1 a). The prisms were used for cutting samples of the following dimensions 1.5 × 30 × 50 mm corresponding to radial, tangential and longitudinal directions, respectively. The samples obtained from each prism were divided into 2 groups in the way presented in Figure 1 b. The first group of the samples was subjected to steaming in a laboratory steaming kiln using treatment parameters typical for industrial conditions (temperature 85°C, treatment time 36 h). The second group consisted of twin samples which were stored without steaming and protected against drying in order to prevent their high initial moisture content (this group of samples will be called as unsteamed samples). The dimensions of the samples were selected in order to ensure obtaining the equilibrium with moist air within 24 to 48 h. The maximum value of the relative error of moisture content determination was the additional criterion of the dimension selection of the samples. The minimum mass of a sample was determined using the approach proposed by Jaros et al. (1994).

The sorption experiments were performed in the set-up schematically presented in Figure 2. The steamed as well as unsteamed samples were placed in the inner

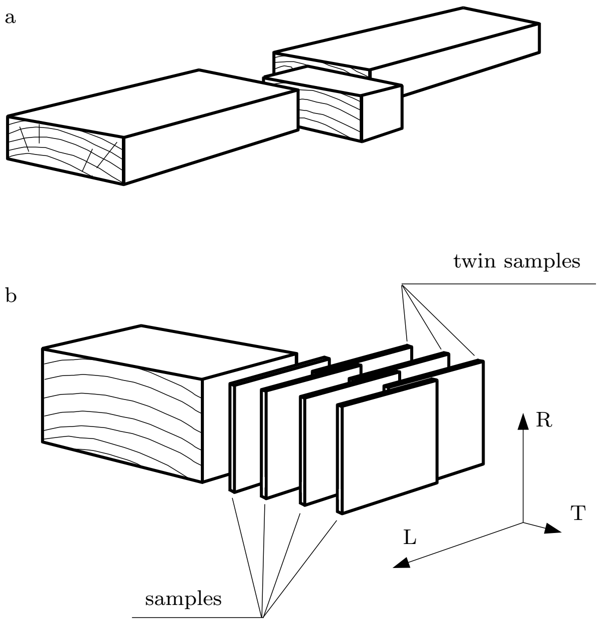

Fig. 1. Scheme of samples preparation

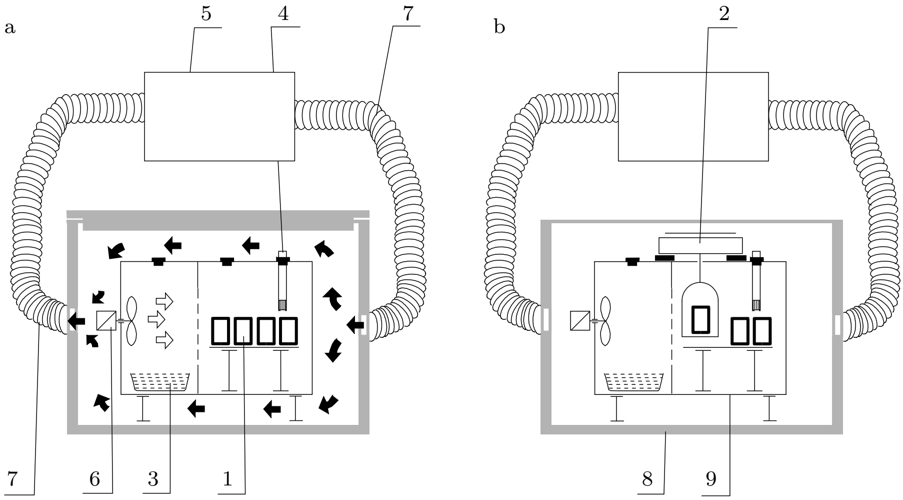

Fig. 2. Scheme of the set-up for sorption experiments: a – equilibration of wood samples, b – weighing of equilibrated samples (1 – wood samples, 2 – balance, 3 – container with salt solution, 4 – thermohygrometer, 5 – heat source, 6 – fan, 7 – ducts of air circulation, 8 – outer chamber with isolation, 9 – inner chamber)

chamber of the set-up. Air circulation in the inner chamber was forced by the fan, while the relative humidity was controlled by a salt solution. The air temperature and relative humidity were measured by the thermohygrometer. The obtained results were stored by the data acquisition system. The inner chamber was encased in the outer chamber isolated with panels made of polystyrene foam. During the equilibration phase of the wood samples the outer chamber was closed and air of controlled temperature was circulating between the heat source and the outer chamber. Air from the outer chamber was heating up the inner chamber however, it was not mixing with air directly contacting with the samples. During the weighing phase of the samples, the upper part of the outer chamber was removed and the balance was placed on the top of the inner chamber. A string was used to link the balance and a pan which was placed inside in the inner chamber. Therefore, the air exchange between the inner chamber and outside was minimized and limited to the weighing phase only.

Air temperature in the inner chamber was equal to 60°C. The application of salt solutions let to obtain six levels of the relative humidity inside the inner chamber. Table 1 contains the list of salt solutions as well as approximated mean values of corresponding relative humidity. The samples were weighed at least twice at each humidity level. After finishing the sorption experiments the samples were placed in a laboratory drier and their oven-dry mass was determined. Each group of samples, i.e. obtained from steamed or unstemed wood, consisted of 11 pieces. Therefore, each value of equilibrium moisture content was the average of 11 measurements.

Table 1. Salt solutions applied in sorption experiments and approximated relative humidity values at temperature of 60°C

Salt solution	H; %
Water (H_2O)	90.0
Sodium chloride (NaCl)	70.7
Sodium bromide (NaBr)	49.9
Calcium chloride ($CaCl_2 \cdot 6\ H_2O$)	34.0
Potassium acetate (CH_3COOK)	20.4
Phosphorus pentoxide (P_2O_5)	3.9

RESULTS OF SORPTION EXPERIMENTS

The sorption data were analyzed by the application of the Hailwood-Horrobin model which predicts the sigmoid type 2 isotherm typical for bound water sorption in wood (Skaar 1988). The model assumes the existence of an ideal solution consisting of dry wood, hydrated wood and dissolved water. The one hydrate form of the model was selected in this study as it is extensively used in wood sorption analyses:

$$M \equiv M_h + M_d = \frac{m_{\text{water}}}{m_{\text{wood}}} \cdot \frac{100 K_1 K_2 H}{100 + K_1 K_2 H} + \frac{m_{\text{water}}}{m_{\text{wood}}} \cdot \frac{100 K_2 H}{100 - K_2 H}$$

where: M – equilibrium moisture content of wood [%],
M_h – hydrated water content [%],
M_d – dissolved water content [%],
m_{water} – molecular mass of water (here 18 kg/kmol) [kg/kmol],
m_{wood} – molecular mass of the dry wood in kg per kmol of sorption sites (i.e. molecular mass of a polymer unit which forms a hydrate) [kg/kmol],
H – air relative humidity [%],
K_1 – equilibrium constant between dissolved water and hydrates,
K_2 – equilibrium constant between dissolved water and water vapor in moist air.

The average values of equilibrium moisture content obtained for the initial sorption of the steamed and unsteamed wood are presented in Table 2. The Hailwood-Horrobin model was separately fitted to both sets of the results. The obtained values of K_1, K_2 and m_{wood} are presented in Table 3. The results were supplemented by values of the coefficient of determination (R^2). The high values of R^2 showed that the model adequately described the desorption. The direct comparison of the fitted values of equilibrium moisture content (M) obtained for unsteamed and steamed wood together with corresponding experimental data is presented in Figure 3.

Table 2. Average values of equilibrium moisture content obtained for initial desorption at 60°C together with measured relative humidity values

Wood treatment	H [%]					
	3.9	20.4	34.0	49.9	70.7	90.0
	M [%]					
Unsteamed wood	0.43 (0.07)	3.63 (0.11)	5.83 (0.10)	8.29 (0.14)	13.85 (0.30)	29.55 (0.54)
Steamed wood	0.28 (0.05)	3.41 (0.08)	5.59 (0.10)	7.87 (0.08)	12.68 (0.13)	28.44 (0.79)

Standard deviations of equilibrium moisture content are given in parentheses.

Table 3. Fitted coefficients of the Hailwood-Horrobin model for the initial desorption of steamed and unsteamed beech wood

Wood treatment	m_{wood}	K_1	K_2	R^2
Unsteamed wood	325.9	4.062	0.912	0.999
Steamed wood	366.1	4.766	0.925	0.999

Some increase in K_1 values was noticed, while K_2 practically did not change its values. The values of K_2 characterized the activity of the dissolved water. The obtained values were lower than unity which meant that the mobility of the dissolved water kept in cell walls was lower as compared to the liquid water. The m_{wood} values slightly increased after wood steaming. The increase was related to some reduction of a number of sorption sites which were available in wood. The reduction was probably related to additional organization of cellulose due to

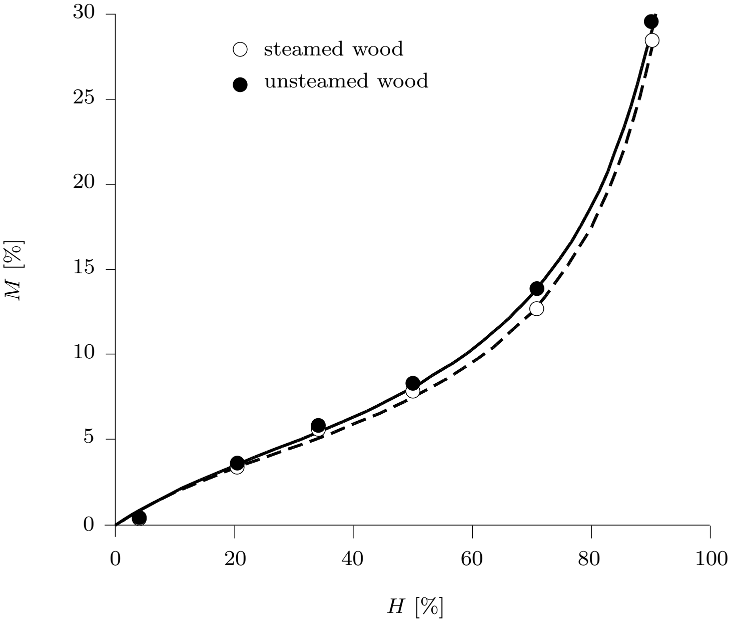

Fig. 3. Comparison of sorption isotherms for unsteamed (solid curve) and steamed (dashed curve) beech wood together with experimental data (dots)

the formation of new bonds in the amorphous part of cellulose and therefore the increase of the crystalline fraction.

The applied approach of the desorption data analysis enabled to determine the fraction of wood which was inaccessible for water. The fraction was calculated as $(m_{\mathrm{wood}} - m_{\mathrm{AGU}})/m_{\mathrm{wood}}$, where m_{AGU} is molecular mass of the anhydrous glucose unit (AGU) and equal to 162 kg/kmol (HARTLEY and SCHNEIDER 1993). The fraction was equal to 0.503 for unsteamed wood, while the value obtained for the wood after steaming was 0.557. The results showed that steaming did not reduce significantly the accessibility of water vapor to the sorption sites in cell walls of wood.

The application of the Hailwood-Horrobin model let to separate the two subsystems of bound water and therefore, to present changes of contents of hydrated water (M_h) and dissolved water (M_d) as functions of air relative humidity. The relations were supplemented with fitted values of equilibrium moisture content (M) and shown in Figures 4 and 5 for unsteamed and steamed wood, respectively. According to SIMPSON (1980) the hydrated water curve is comparable to the monolayer water of the BET model and one water molecule may occupy only one sorption site. The maximum values of the hydrated water contents were practically the same for unsteamed and steamed wood (Table 4). It supports the statement that wood steaming did not reduce the accessibility of water vapor to the sorption sites. The dissolved water corresponds to polymolecularly sorbed water. The contents of this water subsystem differed for unsteamed and steamed wood. The

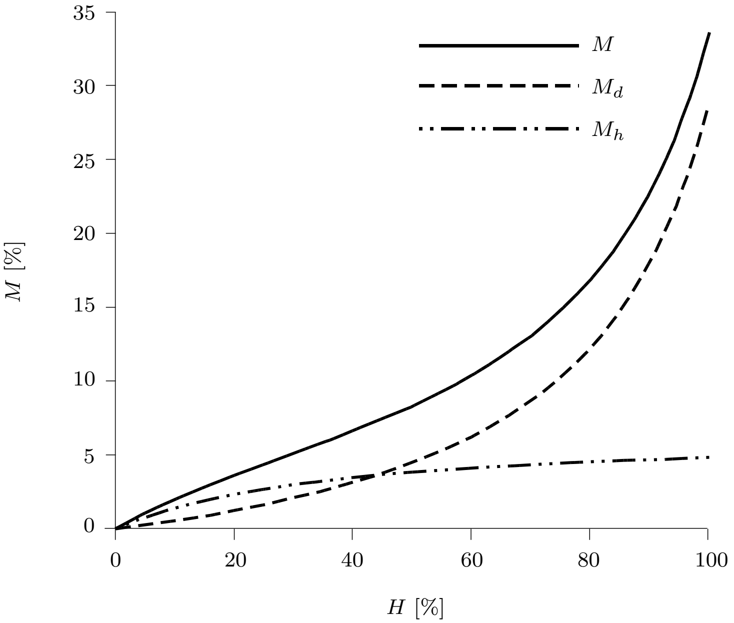

Fig. 4. Equilibrium moisture content (M), hydrated water content (M_h) and dissolved water content (M_d) as functions of air relative humidity for unsteamed beech wood

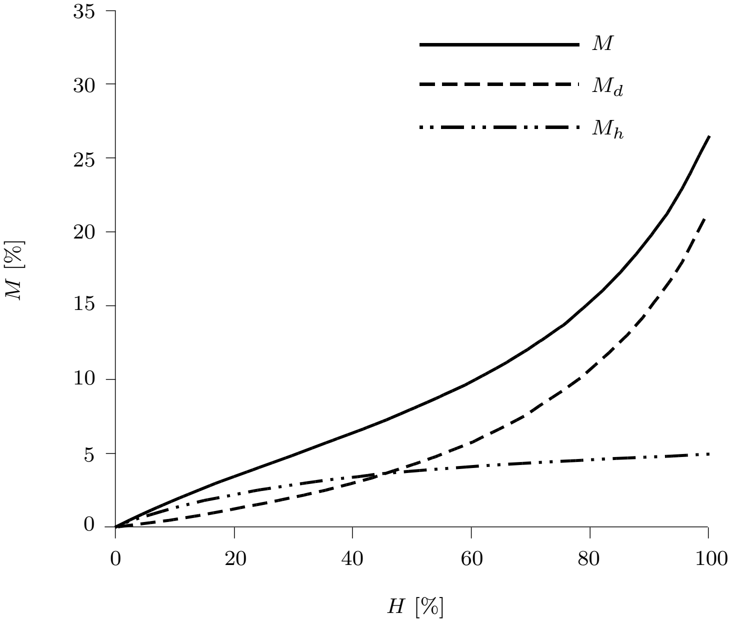

Fig. 5. Equilibrium moisture content (M), hydrated water content (M_h) and dissolved water content (M_d) as functions of air relative humidity for steamed beech wood

difference was most readily seen for the maximum values of the dissolved water content (M_d) presented in Table 4. The reduction of the content was ca. 7% for the steamed wood and it directly influenced the values of the Fibre Saturation Point (Table 4). The lower values of the dissolved water content of wood after steaming had direct influence on the lower equilibrium moisture content values of steamed wood (Fig. 3).

Table 4. The estimated maximum values of hydrated water content (M_h), dissolved water content (M_d) and Fibre Saturation Point (FSP)

Wood treatment	M_h [%]	M_d [%]	FSP [%]
Unsteamed wood	4.87	28.75	33.62
Steamed wood	4.93	21.50	26.43

KILN-DRYING INTENSITY

Drying curves of steamed and unsteamed beech floor strips are presented in Figure 6 a. The moisture content values were registered for industrial processes using the kiln samples method (Dry kiln... 1991). The obtained drying curves showed distinct differences in drying intensities of drying processes for moisture contents above the Fiber Saturation Point. The registered differences are coincident with the earlier observations reported by Harris et al. (1989) who found that drying intensity of steamed oak floor strips is higher as compared to unsteamed ones.

The observed in the present study drying differences are even more readily seen when calculating drying rates and presenting them as functions of drying time (Fig. 6 b). During the initial stage of drying processes the drying rate for steamed flooring strips was as high as 1.5%/h while for unsteamed strips only 0.5%/h. Therefore, it may be stated that the application of the same drying schedule for steamed and unsteamed beech wood is improper. The undesirable increase of drying intensity in the initial stage of drying, i.e. for moisture content higher than the Fiber Saturation Point, stands in contradiction to the principles of timber kiln drying. As it was already observed in industrial conditions it causes different drying defects and significant reduction of the drying quality.

RECOMMENDATION ON DRYING SCHEDULES MODIFICATION

The drying processes analyzed in the present study were carried out for the drying schedule characterized by the constant values of air temperature and drying gradient for moisture content higher than the Fiber Saturation Point. The following parameters were applied in the schedule – the dry-bulb temperature $t = 60°\mathrm{C}$ and drying gradient $DG = 2.1$. When taking into consideration the definition of the

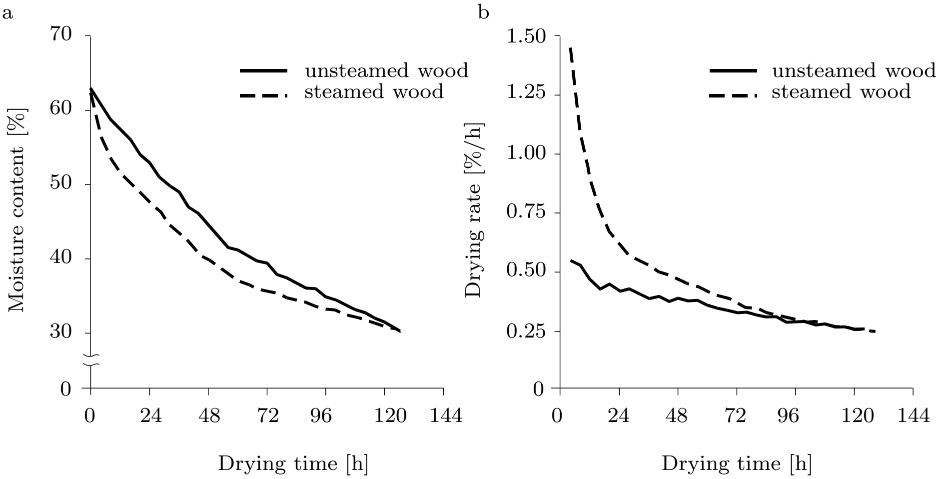

Fig. 6. Drying curves (a) and drying rates (b) of steamed and unsteamed beech flooring stripes

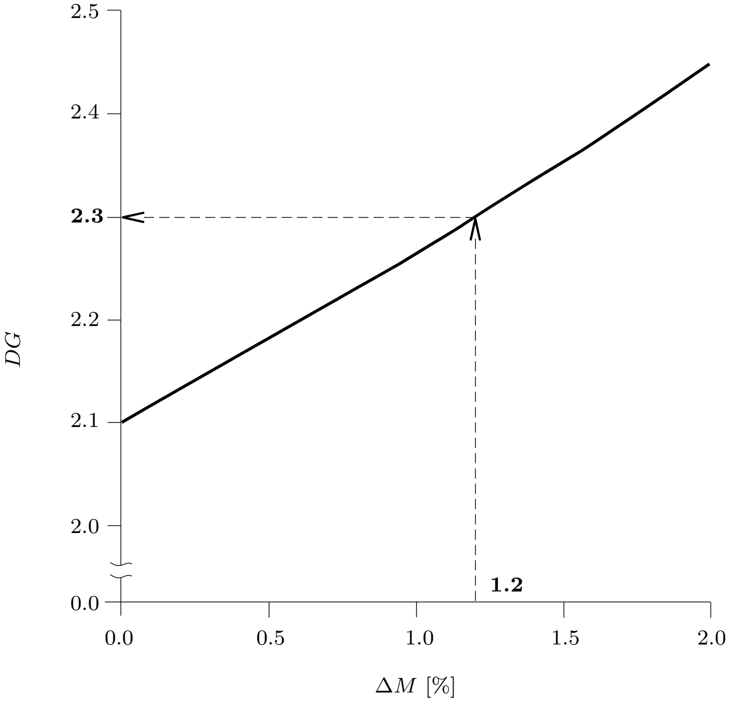

Fig. 7. Correction of drying gradient values accounting changes in sorption properties of steamed wood

drying gradient the equilibrium moisture content can be calculated as follows $M = 30/DG = 30/2.1 \approx 14.3\%$. It corresponds to the relative humidity of drying air of ca. 70% when the equilibrium moisture content values for unsteamed wood are considered (Table 2). At this level of the relative humidity the observed difference in equilibrium moisture content values for unsteamed and steamed wood (ΔM) was ca. 1.2%. Therefore, the estimated drying gradient increase is ca. 2.3 (Fig. 7). Moreover, the recommendation on the drying schedule modification should also consider the higher drying intensity of steamed wood reported in the previous section. Therefore, the reduction of the drying gradient values should be at least 0.3-0.5 when the schedule is applied for drying steamed wood.

CONCLUSIONS

1. Beech timber steaming before drying influences wood sorption properties. The significantly lower equilibrium moisture content values are observed after steaming.
2. The application of Hailwood-Horrobin model in the sorption properties analysis let to found that the decrease of the values of the equilibrium moisture content can be related to the reduction of the dissolved water content. Moreover, beech wood steaming was not causing changes in the accessibility of water vapor to the sorption sites in cell walls of wood and the hydrated water contents were practically the same for unsteamed and steamed wood.
3. The reduction of the dissolved water content of steamed wood caused the significant decrease of the Fiber Saturation Point values of ca. 7%.
4. Kiln-drying of steamed flooring strips should be performed with the use of modified drying schedules. The modification should take into account lower values of the equilibrium moisture content after steaming as well as higher drying intensity. It is recommended to change the schedules in the initial stage of drying, i.e. for the mean moisture contents above the Fiber Saturation Point. The reduction of the drying gradient should be at least 0.3-0.5.

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Received in July 2007

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