Drewno 2014, Vol. 57, No. 191
DOI: 10.12841/wood.1644-3985.052.03

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DETERMINATION OF MOISTURE CONTENT CHANGES IN KILN-DRIED SCOTS PINE TIMBER DURING STORAGE

*The sorption isotherms of Scots pine (*Pinus sylvestris *L.) wood were determined. The experiments were carried out for wood previously dried in industrial batch and progressive kilns according to various drying schedules. The experiments performed made it possible to determine the influence of different drying technologies, as well as parameters, on the sorption characteristics of kiln-dried Scots pine wood. The relationship between the sorption hysteresis and changes in the moisture content of seasoned wood was found. Practical guidelines for equalizing the spread of the final moisture content of individual boards forming a stack were proposed.*

Keywords: sorption isotherm, moisture content spread, drying quality, kiln drying

Introduction

Industrial timber kiln drying usually results in a spread of the final moisture content of individual boards forming a stack. The moisture content spread can be significantly reduced when timber is stored in an environment of controlled air parameters, i.e. temperature and relative humidity. The proper selection of air parameters during timber seasoning after drying depends, among other factors, on the relation between the target and final moisture content values, sorption hysteresis etc. [Salin 2010]. In the case of the mean final moisture content being lower than the target moisture content, the air parameters during storage should be selected in such a way that the first adsorption isotherm is taken into account. Unfortunately, due to a lack of experimental data for different wood species, and sorption phases, as well as the effect of hysteresis, the values of wood equilibrium moisture content (*EMC*) are usually calculated from sorption isotherms without distinguishing

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between adsorption and desorption. Moreover, these isotherms were obtained for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) wood considered to represent the mean sorption characteristics of U.S. wood species [Wengert 1976]. It is also well known that the (*EMC*) is reduced by wood thermal treatment [Kollmann 1963; Kubojima et al. 2003]. Skaar [1988] pointed out that kiln-dried wood had a lower final *EMC* than either green or air-dried wood, and that the higher the temperature during drying, the lower the final *EMC*. Recently, it was observed that there was a tendency to increase kiln drying temperatures beyond 80°C. Gjerdrum [2008] suggested that the *EMC* values tabulated in the Forest Products Laboratory, Madison U.S.A. [Wood Handbook 1955] might be somewhat too high when determining the *EMC* for timber dried in modern kilns. According to Gjerdrum [2008], the *EMC* values for spruce timber kiln-dried at 85°C are on average 95% lower than the data reported in the Wood Handbook. Such differences in *EMC* values may cause problems in the correct determination of wood moisture content after drying. Ahmet et al. [1999] compared the results of sorption experiments for two wood species, i.e. beech and spruce, as well as green, air-dried and kiln-dried wood samples. The *EMC* values obtained were always lower than the reference data from the Wood Handbook. It was concluded that the observed differences resulting from the drying history were small and on average equal to ca. 0.5%. However, the highest *EMC* differences of 2% were observed for relative air humidity above 90%. In the case of kiln-dried spruce wood, the highest differences were found for a much lower relative air humidity of 65%. Moreover, Riehl and Welling [2005] stated that reversed air flow during kiln drying is responsible for oscillations in air temperature and relative humidity, and therefore for a variation in *EMC* values in the inlet and outlet faces of a stack. It was observed that the *EMC* variation was as high as 3% for spruce wood. Stamm and Loughborough [1935] reported that oscillations in relative air humidity caused alternate desorption and adsorption. It resulted in the establishing of an intermediate equilibrium state. Therefore, the oscillating sorption isotherm approached the normal desorption curve at high relative humidity, and the adsorption curve at low relative humidity. According to other studies, the drying data obtained under industrially-controlled conditions gave sorption isotherms which fell within the sorption hysteresis loop. When considering the factors already discussed, it can be expected that the sorption isotherms of timber dried in progressive kilns should be different from the ones obtained for wood dried in batch kilns. This is primarily due to the fact that progressive kilns are characterized by air flow without fan reversion.

The primary objective of the study was to determine the sorption isotherms of Scots pine (*Pinus sylvestris* L.) wood previously dried according to various drying schedules in industrial batch as well as progressive kilns. The secondary objective was the application of the data obtained to improve the prediction of time and moisture content changes during the storage of timber after drying.

Materials and methods

The investigations were made for Scots pine (*Pinus sylvestris* L.) wood. Four twin boards with dimensions: 50 mm thick, 150 mm wide and 4 m long were obtained from a green log (moisture content above the fiber saturation point). Immediately after sawing the boards, they were marked and three of them were placed in three different stacks. The fourth board was not dried. Then, the prepared stacks were placed into the three selected convective driers. The final moisture content was 12±2% for all the analyzed drying processes. The stacks with the first and second boards were placed in two different batch kilns, in which the drying processes were carried out according to the assumptions of a mild schedule (a maximum drying temperature of 55°C) and a severe schedule (a maximum drying temperature of 85°C). The stack with the third board was placed in a progressive kiln, in which the drying process was carried out according to the assumptions of a severe schedule (a maximum drying temperature of 85°C). In the case of the drying in the batch kilns, the investigated board was located in an outer face of the stack which is the most susceptible to the air parameter oscillations due to reversed air flow [Riehl, Welling 2005]. Immediately after the end of each drying process, 13 subsamples measuring 1.5 × 30 × 50 mm, in the radial, tangential and longitudinal direction respectively, were cut from the middle part of each board. Twin samples were obtained from the fourth board (not dried). All samples were stored in a desiccator and dried over phosphorus pentoxide (P_2O_5) in order to obtain an oven-dry state. The adsorption and desorption experiments were carried out in the previously prepared test set-up, in which the wood samples were placed in a chamber, while the relative humidity was controlled by salt solutions [Majka, Olek 2007]. The air temperature and relative humidity were measured by a thermo-hygrometer. The application of salt solutions made it possible to obtain nine levels of relative humidity inside the chamber. All the samples were weighed at least twice after obtaining the equilibrium at each humidity level. The results obtained were stored by the data acquisition system. At the end of the sorption experiments, all the samples were placed in a laboratory drier and their oven-dry mass was determined. The sorption isotherms were determined at 22±1°C in order to apply the results obtained from the sorption experiments to determine the *EMC* values during timber seasoning after kiln drying. The sorption data were approximated using the Hailwood-Horrobin two-hydrate (n = 2) model [Hailwood, Horrobin 1946]:

$$EMC = \frac{18}{W}\left(\frac{KH}{1-KH} + \frac{K_1KH + 2K_1K_2K^2H^2}{1 + K_1KH + K_1K_2K^2H^2}\right) \tag{1}$$

where: H is the relative humidity of air and W, K, K_1, K_2 are the parameters of the equation (1).

For the purpose of comparison, the parameters of the Hailwood-Horrobin model were also calculated according to the procedure proposed by Simpson [1973] with the assumption that temperature (t) is equal to 22°C:

$$W = 349 + 1.29 \cdot t + 0.0135 \cdot t^2 \tag{2}$$

$$K = 0.805 + 0.000736 \cdot t - 0.00000273 \cdot t^2 \tag{3}$$

$$K_1 = 6.27 - 0.00938 \cdot t - 0.000303 \cdot t^2 \tag{4}$$

$$K_2 = 1.91 + 0.407 \cdot t - 0.000293 \cdot t^2 \tag{5}$$

SigmaPlot 9.0 software with the implemented Levenberg-Marquardt iterative algorithm was applied in order to find the coefficients of the model of the investigated sorption isotherms.

The experimental data obtained and the results of the modeling were compared. The comparison criterion was defined as follows:

$$\Delta EMC = EMC_{FPL} - EMC_e \tag{6}$$

where: EMC_{FPL} and EMC_e are equilibrium moisture content values modeled with the Hailwood-Horrobin equation (1–5) and experimental data, respectively.

In order to determine the influence of drying temperature and kiln type on the hystersis phenomenon, the hysteresis ratio was determined, calculated as:

$$\frac{EMC_{ads}}{EMC_{des}} \tag{7}$$

Moreover, in order to verify the correctness of the assumptions from the common practice of using a set of FPL sorption data [i.e. Wood Handbook 2010] in determining the *EMC* of wood during timber post-drying storage, as well as the effect of the sorption hysteresis phenomenon on the changes in the moisture content of the timber, an additional experiment was carried out under industrial conditions. The experiments consisted of registering changes in the moisture content of already dried 25 mm Scots pine timber. Before starting these experiments, boards were sorted into two groups (each group consisted of 20 boards). The first group of boards was characterized by a moisture content of 8%, lower than the target moisture content after kiln drying, while the second one had a higher moisture content of 16%. The measurements of moisture content were made using a Brookhuis® FME meter equipped with isolated pins according to the PN-EN 13183-2::2004 standard. The storage phase was studied under industrial conditions and the air parameters were as follows: temperature 20±2°C, relative humidity 55±5%.

Results and discussion

Fig. 1 presents the sorption data approximated by the Hailwood-Horrobin model. The post-kiln isotherms of Scots pine timber obtained during the experiments were significantly different from the sorption curves derived from the FPL data fitted by Simpson [1973].

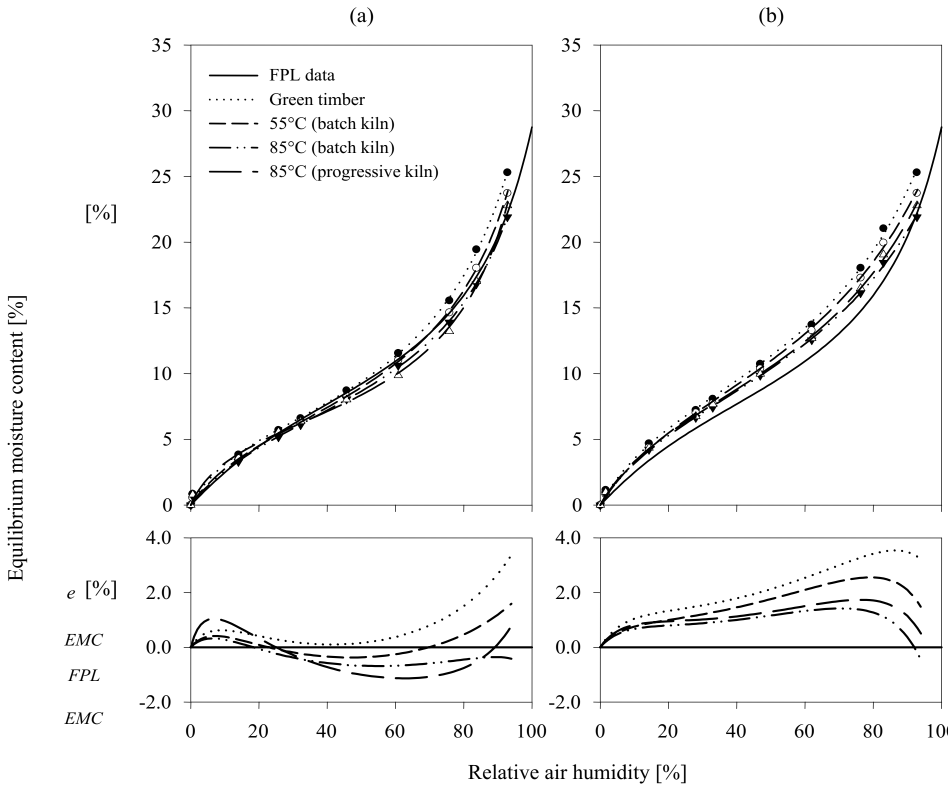

Fig. 1. Sorption isotherms of green and dried Scots pine (*Pinus sylvestris* L.) at 22±1°C. Upper plots – measured data and results of modeling using Hailwood-Horrobin (n = 2) equation for (a) 1st adsorption, (b) 2nd desorption. Bottom plots – EMC differences between measured data and results of modeling

The observed differences were particularly high for the desorption phase (fig. 1b). However, it was found that the *EMC* values of green and kiln-dried Scots pine timber as estimated using the Hailwood-Horrobin model were always higher than the corresponding *EMC* values reported in the Wood Handbook [2010]. These observations were valid for the entire range of relative air humidity under consideration, i.e. 0–90%.

Table 1 summarizes the values of the estimated coefficients of the Hailwood--Horrobin sorption model. The values of the coefficients clearly depend on the sorption phase as well as the parameters of prior drying. The values of the determination coefficient (R^2) indicate the very high capacity of the model to approximate the empirical data.

Table 1. Estimated coefficients of Hailwood-Horrobin (n = 2) sorption model fitted to the FPL data [Simpson 1973] and *EMC* data determined for green and dried Scots pine timber (temperature of 22±1°C)

Timber	Kiln type	Drying temperature [°C]	Sorption phase	Coefficients of sorption model				R^2
				K	K_1	K_2	W	
Dried	batch	55°C	Ads. Des.	0.8372 0.6930	8.170 5.455	1.142 0.0123	367.1 194.8	0.9997 0.9995
Dried	batch	85°C	Ads. Des.	0.8282 0.6877	7.786 6.138	1.591 0.1064	391.6 214.1	0.9994 0.9997
Dried	progressive	85°C	Ads. Des.	0.8749 0.7087	16.00 6.640	2.216 0.0789	465.9 218.3	0.9986 0.9995
Green	–	–	Ads. Des.	0.8150 0.7234	8.104 6.430	0.0959 0.0481	286.1 203.4	0.9993 0.9991
Green*	–	–	–	0.8199	5.917	2.664	383.9	–

* FPL data for Sitka spruce

Table 2 presents the estimated values of the *EMC* for Scots pine timber during after-drying storage at typical levels of relative humidity (RH). The similarity of the estimated empirical data with the FPL sorption data was observed only in the case of the Scots pine timber dried at 55°C in a batch kiln (1st adsorption). In the other cases, the compared data varied greatly – especially for the 2nd desorption. Comparison of the *EMC* values for the dried pine timber with the *EMC* values typical for the green timber (not dried) indicated that the higher the temperature of drying, the greater the reduction in the wood *EMC*. However, the difference between the adsorption and desorption *EMC* values for the same storage climate (sorption hysteresis phenomenon) was at a level of approx. 2%, regardless of the drying parameters.

The values of the hysteresis ratio as calculated with Eq. (7) are presented in fig. 2. The ratio was determined with the data obtained for the kiln-dried 50 mm Scots pine timber. The insignificant differences in the ratio values were found for the timber dried in the batch kilns with the application of mild and severe drying schedules, i.e. drying temperatures of 55 and 85ºC, respectively (fig. 2a). It can be concluded that the drying temperature has a minor influence on the hysteresis phenomenon in kiln-dried timber. In contrast to that, the values of the hysteresis ratio obtained for the timber dried at 85ºC in the batch and progressive kilns were significantly different (fig. 2b). This allowed the conclusion that the oscillations of air parameters in the batch kilns reduced the unfavorable hysteresis phenomenon.

Table 2. Selected *EMC* values calculated from the Hailwood-Horrobin (n = 2) sorption model fitted to the FPL data, green and dried Scots pine timber (storage conditions: temperature 20±2°C, relative humidity 55±5%)

Timber	Kiln type	Drying temperature [°C]	Sorption phase	Relative air humidity [%]				
				40	45	50	55	60
				Equilibrium moisture content [%]				
Dried	batch	55	Ads.	7.4	8.2	8.9	9.8	10.7
			Des.	9.1	10.0	11.0	12.0	13.0
Dried	batch	85	Ads.	7.2	7.9	8.7	9.5	10.3
			Des.	8.7	9.5	10.4	11.3	12.3
Dried	progressive	85	Ads.	7.1	7.7	8.4	9.1	9.9
			Des.	8.8	9.6	10.5	11.4	12.4
Green	–	–	Ads.	7.8	8.6	9.4	10.3	11.3
			Des.	9.5	10.4	11.3	12.4	13.5
Green*	–	–	–	7.7	8.4	9.2	10.0	10.9

* FPL data for Sitka spruce

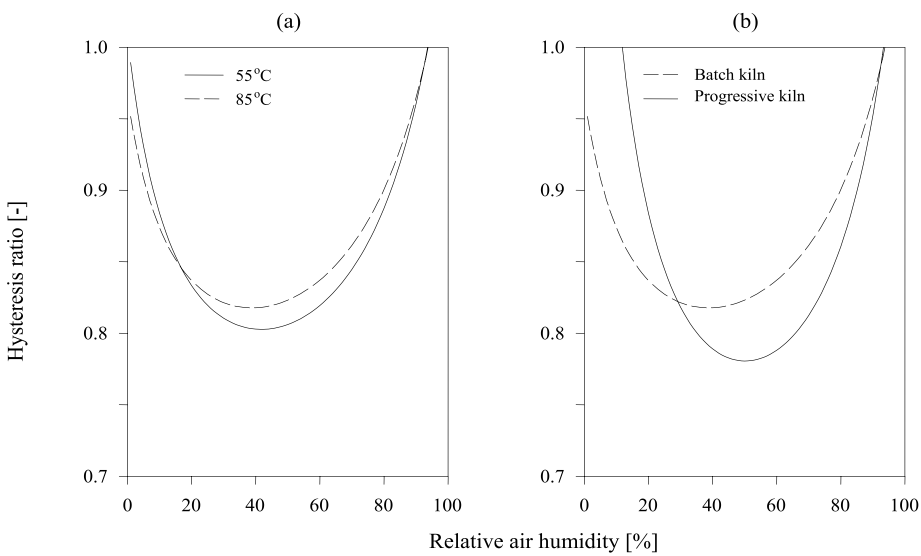

Fig. 2. Hysteresis ratio for *EMC* data obtained for 50 mm Scots pine timber (a) drying process in the batch kiln according to the mild schedule (temperature of 55°C) and the severe schedule (temperature of 85°C), (b) drying process in a batch kiln and a progressive kiln (temperature of 85°C)

Fig. 3 illustrates the changes in the moisture content of the 25 mm dried Scots pine timber, which was stored after drying for a period of 4 weeks under conditions which resulted in a reduction of the spread of timber moisture content. In spite of a long storage period due to the sorption hysteresis phenomenon, the moisture content of the dried timber (MC approx. 8% and 16%) did not reach the target MC of 10% (table 2), which can be calculated using the procedure of Simpson [1973] based on the intermediate sorption data for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) [Wood Handbook 2010]. Moreover, a different course and scope of changes in the moisture content of timber which was too dry (below the target MC) and timber which was too wet (above the target MC) were observed (fig. 3).

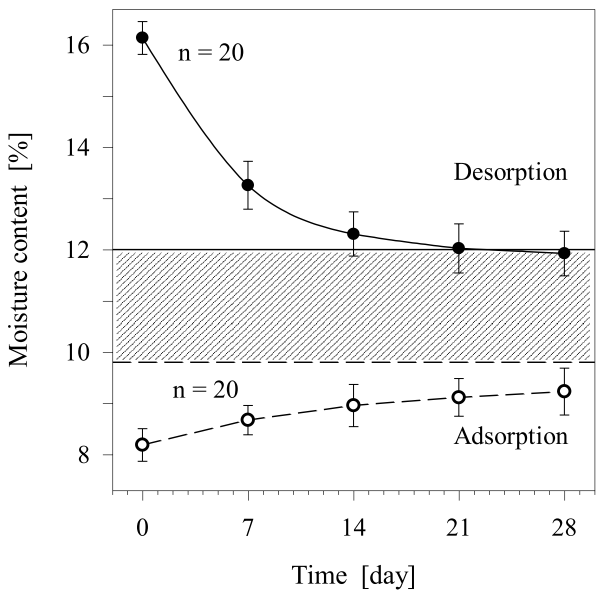

Fig. 3. Moisture content changes of 25 mm Scots pine timber dried at a temperature of 55°C (target MC = 10%) during storage at temperature of 20±2°C, RH = 55±5%, (striped area – sorption hysteresis, solid line – target MC for desorption phase, dashed line – target MC for adsorption phase)

Conclusions

1. The kiln drying of the timber caused permanent changes in the hygroscopic properties of the wood. Whereby, the drying temperature had a greater impact on the reduction of the equilibrium moisture content of the wood than the drying process (e.g. batch or progressive kilns).
2. The oscillations of air parameters due to reversed air flow in the batch kilns had a more significant influence on the reduction of the hysteresis phenomenon than the drying temperature according to the mild and severe schedules, respectively.

3. In order to determine air parameters for the after-drying storage of timber it is necessary to take into account the sorption hysteresis phenomenon. Thus, the procedure proposed by Simpson [1973] has very limited application when timber with excessive moisture content spread has to seasoned.
4. Sorption hysteresis phenomenon, as well as the different course and extent of changes observed in the moisture content of dried timber (below and above target MC), is the basis for concluding that the after-drying storage of timber with the wrong moisture content should not be carried out under the same climate conditions (temperature and relative humidity of the air).

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List of standards

PN-EN 13183-2:2004 Wilgotność sztuki tarcicy. Część 2: Oznaczanie wilgotności za pomocą elektrycznego wilgotnościomierza oporowego (Moisture content of a piece of sawn timber. Pont 2: Estimation by electrical resistance method)

WYZNACZANIE ZMIAN WILGOTNOŚCI WYSUSZONEJ TARCICY SOSNOWEJ PODCZAS JEJ KLIMATYZOWANIA

Streszczenie

Celem pracy było wyznaczenie izoterm sorpcji drewna sosny pospolitej (*Pinus sylvestris* L.) uprzednio wysuszonego w warunkach produkcyjnych oraz określenie wpływu technologii suszenia na przebieg i zakres zmian wilgotności tarcicy podczas jej klimatyzowania bezpośrednio po suszeniu. W badaniach zostały uwzględnione różne warianty realizacji konwekcyjnego procesu suszenia tarcicy sosnowej. Uwzględniono również warunki odpowiadające założeniom łagodnego (maksymalna temperatura suszenia 55°C) i intensywnego programu suszenia (maksymalna temperatura suszenia 85°C). Ponadto procesy suszenia zostały zrealizowane w suszarkach o odmiennej konstrukcji, tj. suszarce komorowej i tunelowej. Stwierdzono ograniczoną przydatność wartości wilgotności równowagowej drewna opublikowanych w *Wood Handbook*, powszechnie uznawanych jako referencyjne, do prawidłowego określania zakresu zmian wilgotności tarcicy sosnowej po suszeniu, z uwagi na różnice z uzyskanymi danymi empirycznymi oraz brak możliwości uwzględnienia zjawiska histerezy sorpcji. Stwierdzono również, że realizacja procesu konwekcyjnego suszenia tarcicy sosnowej powoduje tym wyższe obniżenie jej wilgotności równowagowej po suszeniu im wyższa była temperatura powietrza podczas suszenia. Natomiast charakterystyczne dla realizacji procesu suszenia tarcicy w suszarkach komorowych oscylacyjne zmiany parametrów powietrza, wywołane rewersyjnymi zmianami kierunku przepływu powietrza, powodują zmniejszenie zjawiska histerezy sorpcji. Zebrane informacje nt. wilgotności równowagowej i zjawiska histerezy sorpcji wysuszonego drewna sosny można wykorzystać do zwiększenia efektywności klimatyzowania tarcicy sosnowej bezpośrednio po suszeniu.

Słowa kluczowe: izotermy sorpcji, rozrzut wilgotności, jakość suszenia, suszenie konwekcyjne