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ORIGINAL ARTICLE

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Effect of EMC and air in wood on the new in-process moisture content monitoring concept under radiofrequency/vacuum (RF/V) drying

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Abstract To improve the accuracy of the new in-process moisture content (MC) monitoring concept under radiofrequency/vacuum (RF/V) drying, equilibrium moisture content (EMC) tests were carried out under various ambient pressures, and pressure curves in wood were analyzed during chamber evacuation and heating phases. The results showed that EMC increased with a decrease in ambient pressure regardless of temperature, relative humidity (RH), and species. The accuracy of MC estimation for Hinoki under RF/V drying was improved from 1.5% maximum absolute errors to 0.6% after EMC modification. The pressure curves for Hinoki and Sugi under RF/V drying showed similar tendencies to an idealized process. Russian larch showed different curves, indicating that the pressure in the wood did not reach the ambient pressure because of its low permeability. Therefore, MC could not be estimated using this monitoring concept because of the presence of much air in the wood of Russian larch.

Key words In-process estimation of moisture content · Radiofrequency/vacuum drying · EMC under vacuum conditions

Introduction

Over the past few decades, the use of vacuum drying has been steadily increasing (especially for drying of valuable species) and is likely to continue increasing as a rapid drying method.[1] As with conventional drying, it is important to know moisture content (MC) during vacuum drying to program appropriate schedules, control costs and quality, as well as to investigate vacuum drying mechanisms. However, until now, there have only been a few methods to measure MC under radiofrequency/vacuum (RF/V) drying. The method of Koumoutsakos et al.[2] can only measure the average moisture content and cannot avoid the impact of uncondensed water vapor. Although Cai's concept[3] can monitor moisture content and distribution by detecting temperature and pressure in wood and the relationship between temperature, relative humidity (RH), and equilibrium moisture content (EMC), he assumed that the pressure detected by sensors was just water vapor pressure and that EMC was constant at any ambient pressure in all wood species. However, air was present in the tube of the sensor complex and the wood itself during Cai's RF/V drying tests.[4] If the air cannot be completely removed from the wood, it will affect the pressure detected by the sensors during the whole drying process and, consequently, his approach will result in incorrect moisture content estimation.

In conventional drying, EMC is related to the temperature and relative humidity of the air, and it is also affected by species, extractive content, and other factors.[5] EMC under vacuum conditions has been reported by Chen et al.[4] and Yi et al.:[6] Chen provided a theoretical estimate for EMC but without experimental evidence to support his assumption, while Yi obtained experimental results that had obvious differences to Chen's theoretical EMC. Both studies showed that EMC under vacuum conditions was different from EMC obtained under atmospheric pressure. In addition, neither reported the relationship between EMC and temperature, relative humidity, and ambient pressure, which is the basis of the new MC monitoring concept. Therefore, in this study, to investigate the effect of air in wood and EMC on this concept, EMC tests under various pressures and RF/V drying tests under a pressure of 6.7 kPa were conducted for designated species.

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Materials and methods

EMC tests under vacuum conditions

Samples

Materials used were Hinoki (*Chamaecyparis obtusa*, 0.40 g/cm³, 37.1% initial MC) and Russian larch (*Larix gmelinii*, 0.51 g/cm³, 47.8% initial MC). Both were processed into end-matched EMC test samples with dimensions of 0.5 (L) × 3.0 (T) × 3.0 (R) cm.

Method

The condition of 60°C and 50% relative humidity was chosen in this test. The temperature and RH were kept constant throughout the test: only the ambient pressure was varied. The samples (five pieces each of Hinoki and Russian larch) were subjected to an ambient pressure of 13.4 kPa (100 Torr) for several days. After the weight of the samples became constant, the ambient pressure was changed to 33.4 kPa (250 Torr). After the weight again became constant, the ambient pressure was changed to 56.3 kPa (400 Torr), and finally to 101.3 kPa (760 Torr).

Relative humidity calculation under vacuum conditions

Under vacuum conditions, partial vapor pressure (P) is calculated by Eq. 1[7,8] and relative humidity (ϕ) by Eq. 2 as shown below. It can be seen from Eqs. 1 and 2 that relative humidity is affected by ambient pressure, even we if control constant dry-bulb and wet-bulb temperatures.

$$P = P_{ow} - \frac{(P_a - P_{ow})(C - C_w)}{1546 - 1.44C_w} \quad (1)$$

$$\phi = \frac{P}{P_s} \times 100\% \quad (2)$$

where P is partial vapor pressure (Pa), P_{ow} is saturated vapor pressure at wet-bulb temperature (Pa), P_a is ambient pressure (Pa), P_s is saturated pressure at dry-bulb temperature (Pa), C is dry-bulb temperature (°C), and C_w is wet-bulb temperature (°C).

Radiofrequency/vacuum drying tests (estimation of moisture content)

Samples

Hinoki, Russian larch, and Sugi (*Cryptomeria japonica*, 41.8% initial MC) box-heart square timbers (see Fig. 1) with dimensions of 85 (L) × 12 × 12 cm were used for RF/V drying tests. All timbers were sealed on one end by epoxy resin adhesive.

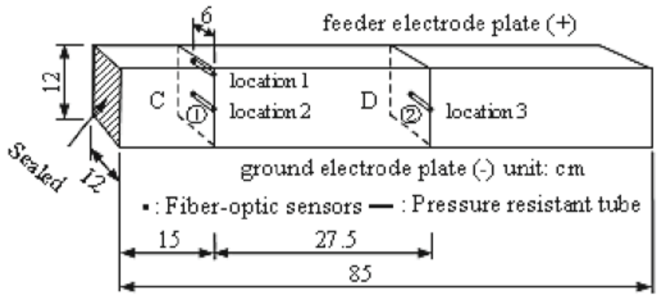

Fig. 1. Dimensions of sample and locations for measurement of temperature and pressure under radiofrequency/vacuum (RF/V) drying. ①, ②, Sections for measurement of temperature, pressure, and moisture content (MC). Temperature was controlled at location 3

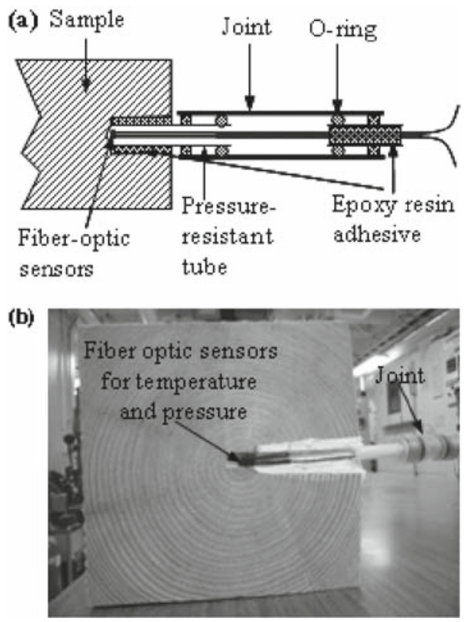

Fig. 2. Temperature and pressure measurement under RF/V drying. **a** Schematic; **b** actual photograph

Measurement system for temperature and pressure

Cai et al. used a sensor complex with oil transmission for pressure measurement and a fiberoptic sensor for temperature measurement. In this study, a new fiberoptic sensor complex measurement system (see Fig. 2) for simultaneous temperature and pressure measurement at the same location was developed. In this measurement system, pressure was also measured by fiberoptic sensors. Temperature and pressure were measured once every 3 min during the drying process at three locations as shown in Fig. 1. (Location 1 was near the sample's surface in section ①, location 2 (close to the sealed end) was in the center of section ①, and location 3 was in the center of section ②.)

Drying conditions

In these experiments, drying temperature (T_c) was controlled at location 3 (see Fig. 1). The drying conditions of all tests

Table 1. Test conditions for eight runs of radiofrequency/vacuum (RF/V) drying

Run no.	Species	Chamber evacuation time (h)	RF load time (h)	P_a (kPa)	T_{sa} (°C)	T_c (°C)	P_{sc} (kPa)	ΔP (kPa)
1	Sugi	15	64	6.7	38	60	20	13.3
2, 3	Sugi	15	72	6.7	38	60	20	13.3
4, 5	Hinoki	12	96	6.7	38	60	20	13.3
6, 7, 8	Russian larch	15	96	6.7	38	60	20	13.3

P_a, Ambient pressure in chamber; T_{sa}, saturated temperature to P_a, T_c, control temperature; P_{sc}, saturated pressure to T_c; ΔP, $P_{sc} - P_a$

are shown in Table 1. Radiofrequency (RF) load was controlled by temperature and time, with the latter having priority. Temperature control means that the RF load was stopped when temperature reached the control temperature T_c and the RF load was restarted when temperature became 2°C lower than T_c. The time control was set as a 9-min RF load and a 1-min unload of RF throughout the entire drying process to avoid overheating. To remove the air in the tube of the sensor complex unit and the wood, the chamber was evacuated for 12–15 h before RF load.

Estimation of moisture content under RF/V drying tests

The moisture content of four runs of drying was estimated based on the new MC monitoring concept, and the data used for the moisture content estimation for each run were the mean of temperature and pressure detected simultaneously at the same location at 30-min intervals.

Results and discussion

EMC under vacuum conditions

The EMC for Hinoki and Russian larch under various ambient pressures can be seen in Fig. 3, which shows that even under the same temperature and RH conditions, EMC increased with a decrease in ambient pressure. Therefore, a regression curve expressed as $y = 0.0003x^2 - 0.0641x + 9.4874$ for Hinoki was obtained for EMC modification in this study.

Pressure process in wood during the whole period

As already mentioned, the methodology of the new MC monitoring concept is based on temperature and pressure detected by fiberoptic sensors. Cai et al. assumed that the pressure detected by the sensors was just water vapor pressure and did not consider the effect of air in the tube and wood. To avoid the effect of air, an idealized process during RF/V drying was proposed in this study (Fig. 4) based on the report of Sasaki et al.[9] on pressure change inside wood. Phase A–B is the process for removing air from the chamber without an RF load. The temperature in the wood is constant during this phase, but pressure decreases to ambient pressure. The period of this phase is related to wood permeability and dimension. If radiofrequency is loaded for

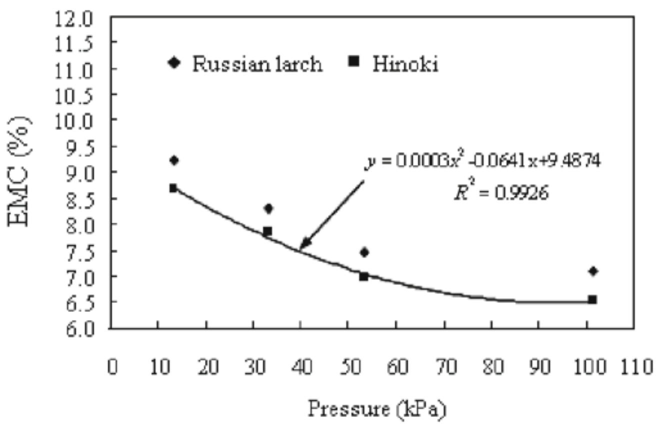

Fig. 3. Equilibrium moisture content (*EMC*) of Russian larch and Hinoki under 60°C, 50% relative humidity (RH), and various pressures

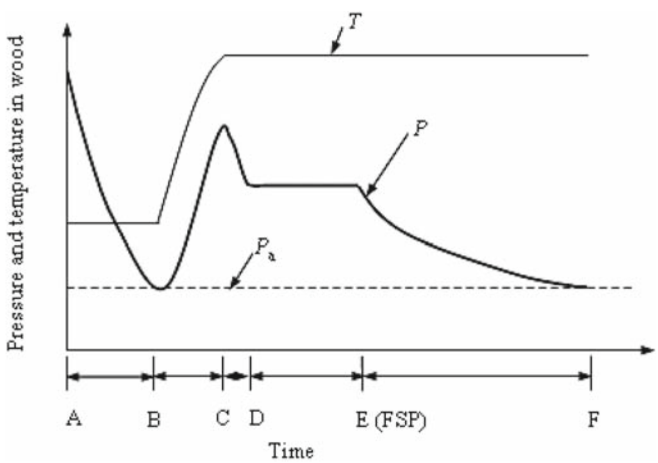

Fig. 4. The idealized process in wood during RF/V drying. *T*, Temperature in wood; *P*, pressure in wood; P_a, ambient pressure in chamber; *A–B*, chamber evacuation phase; *B–F*, RF load phases. *FSP*, fiber saturation point

timber heating at point B, the pressure in the wood increases with the expansion of residual air and water vapor from the presence of free water. Both temperature and pressure climb to a peak at point C. From point C, the temperature remains constant because it is controlled. The pressure then decreases to point D as the residual air is removed during the C–D phase. The pressure maintained by the saturated vapor pressure corresponding to constant temperature remains constant during the D–E phase because of the

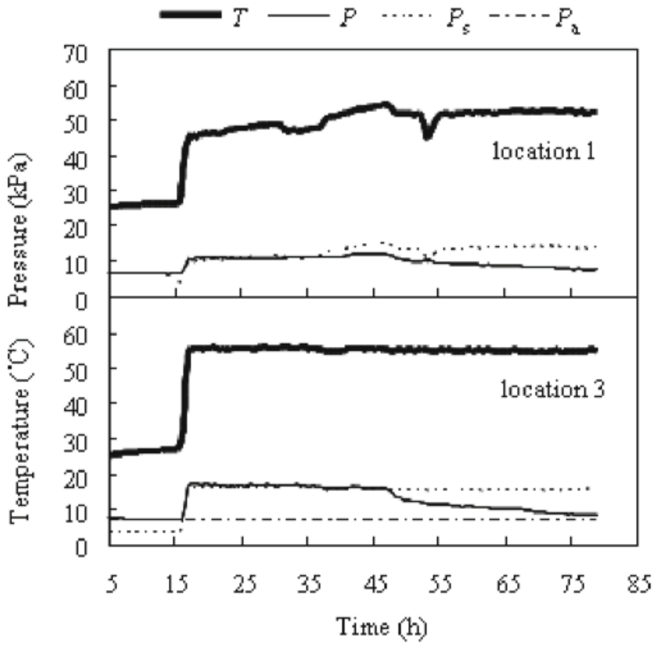

Fig. 5. Temperature, pressure, and saturated pressure curves for locations 1 and 3 during RF/V drying for Sugi run 1 (6.7 kPa, 64 h). *T*, Temperature detected by sensor; *P*, pressure detected by sensor; P_s, saturated pressure corresponding to *T*; P_a, ambient pressure in the chamber

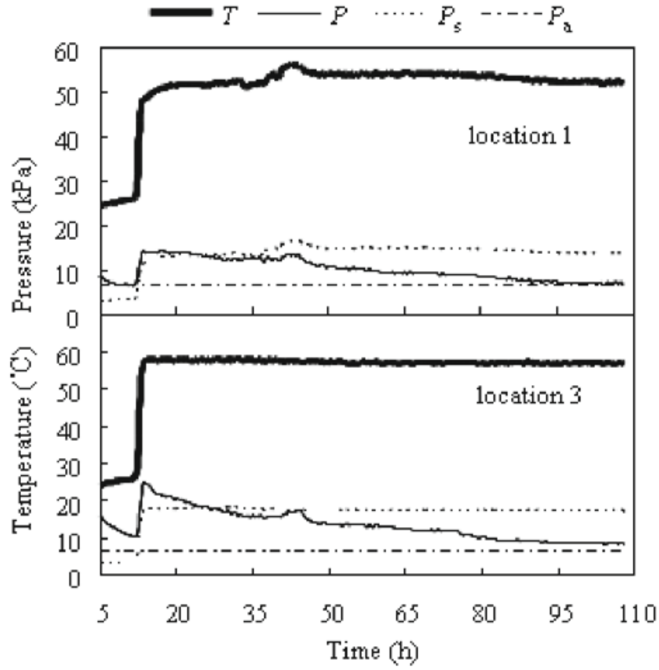

Fig. 6. Temperature, pressure, and saturated pressure curves for locations 1 and 3 during RF/V drying for Hinoki run 4 (6.7 kPa, 96 h). *T*, Temperature detected by sensor; *P*, pressure detected by sensor; P_s, saturated pressure corresponding to *T*; P_a, ambient pressure in the chamber

presence of free water in the wood. As free water disappears at point E, the fiber saturation point (FSP), the pressure in the wood decreases gradually in response to reduction in vapor pressure. Although the pressure decreases, there is no air penetration into the wood because of higher pressure in the wood. However, if drying continues from point F when pressure is equal to ambient pressure, the vapor pressure will be lower than ambient pressure, so ambient air may penetrate into the wood. In this case, the pressure detected is not equal to vapor pressure.

The actual pressure curves for location 1 and location 3 of run 1 in Fig. 5 (Sugi, 6.7 kPa, 64 h) and run 4 in Fig. 6 (Hinoki, 6.7 kPa, 96 h) showed similar tendencies to the idealized process. This finding indicates that we can measure the vapor pressure from the medium stage of drying using this method. However, for Russian larch, the pressure process in the wood was different from that in Sugi and Hinoki and was always higher than the saturated pressure (Fig. 7). It can be seen that the pressure did not remain constant during the experimental period and was higher than saturated pressure even at the end of drying. This result is considered to occur because the air in Russian larch is not completely removed during the drying period. It is known that Russian larch has low permeability, so if we want to apply this new monitoring system to it, more time is required.

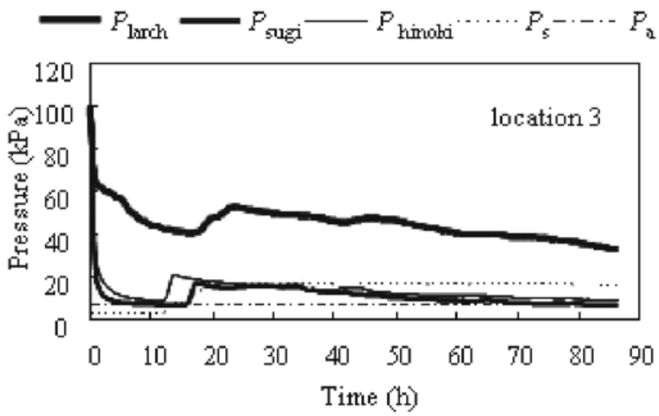

Fig. 7. Pressure curves for location 3 for Russian larch, Sugi, and Hinoki during RF/V drying (6.7 kPa). P_s, Saturated pressure corresponding to *T*; P_a, ambient pressure in the chamber

Moisture content estimation and modification

Moisture content was estimated with the new MC monitoring concept, and the final results of the four drying runs (Sugi and Hinoki) for three locations are presented in Table 2. In the table, moisture content was estimated using the Kollmann et al.[10] EMC chart. The estimated moisture content was always less than that determined by the oven drying method, and the absolute errors ranged from 0.0% to 2.4%. For Russian larch, the MC results cannot be estimated because the pressure detected at the end of drying was higher than the saturated pressure due to the low permeability of Russian larch and residual air in the wood during the whole drying period.

The MC estimated in Table 2 was based on Kollmann's EMC chart for spruce obtained under atmospheric condi-

Table 2. Estimated moisture content and absolute errors for four runs of RF/V drying

Run no.	1			2			3			4		
Measurement locations[a]	1	2	3	1	2	3	1	2	3	1	2	3
MC estimated by Kollmann's EMC (%)	8.7	8.0	8.4	7.6	8.6	6.1	10.0	7.6	7.0	7.9	8.4	7.5
MC determined by oven drying method (%)	9.0	9.8	8.4	8.5	9.2	7.1	11.3	9.5	9.4	9.4	9.4	8.8
Absolute error[b] (%)	0.3	1.8	0.0	0.9	0.6	1.0	1.3	1.9	2.4	1.5	1.0	1.3

EMC, Equilibrium moisture content
[a] Measurement locations are shown in Fig. 1
[b] Absolute error = estimated moisture content – moisture content determined by oven drying method

Table 3. Absolute errors for estimated moisture content before and after equilibrium moisture content (EMC) modified for Hinoki run 4 RF/V drying

Measurement locations	1	2	3
MC determined by oven drying method (%)	9.4	9.4	8.8
MC estimated by Kollmann's EMC (%)	7.9	8.4	7.5
Error 1 (%)	1.5	1.0	1.3
MC estimated by EMC modified for Hinoki (%)	9.7	10.0	9.3
Error 2 (%)	0.3	0.6	0.5

Error 1, MC estimated by Kollmann's EMC – MC determined by oven drying method; Error 2, MC estimated by EMC modified for Hinoki – MC determined by oven drying method

tions. As mentioned earlier, we know the effect of ambient pressure on EMC from the results shown in Fig. 3. Therefore, EMC was modified for corresponding species and ambient pressure to estimate MC precisely. According to the EMC test results under the vacuum conditions described above, the EMC value for Hinoki under a pressure of 6.7 kPa (60°C, 50% RH) was calculated as 9.07% by the equation $y = 0.0003x^2 - 0.0641x + 9.4874$ (see Fig. 3). Based on this value and Kollmann's EMC chart, EMC was modified for Hinoki for an ambient pressure of 6.7 kPa. The MC for Hinoki run 4 was estimated again based on the modified EMC under an ambient pressure of 6.7 kPa; the results (Table 3) showed smaller absolute errors and were within 0.6% compared with the estimated results of Kollmann's EMC chart. If we use the modified EMC for the other runs, the accuracy can be improved because EMC increased with a decrease in ambient pressure.

Conclusion

EMC tests under various pressures and MC estimation for eight runs of radiofrequency/vacuum drying under a pressure of 6.7 kPa using the new MC monitoring concept were carried out on Russian larch, Hinoki, and Sugi. The results are summarized below:

1. EMC was affected by ambient pressure. As ambient pressure decreased, EMC increased more than that indicated by Kollmann's chart.
2. The moisture content estimated from temperature and pressure for Hinoki was smaller than the MC determined by the oven drying method, and the absolute errors ranged from 1.0% to 1.5%.
3. The accuracy of moisture content estimated by the modified EMC was improved, and the absolute errors were within 0.6%.
4. The pressure curves of Hinoki and Sugi were different from Russian larch because of the difference in permeability.

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