J Wood Sci (2007) 53:1–4
DOI 10.1007/s10086-006-0813-4



ORIGINAL ARTICLE

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# New monitoring concept of moisture content distribution in wood during RF/vacuum drying

Received: November 24, 2005 / Accepted: April 10, 2006 / Published online: August 6, 2006

**Abstract** A new method for monitoring moisture content during radio-frequency (RF)/vacuum drying was developed by measurement of temperature and pressure in wood. Temperature and pressure inside the wood were measured simultaneously during RF/vacuum drying at the same point. The relative humidity (RH) and moisture content (MC) below the fiber saturation point (FSP) were calculated based on temperature and pressure, and the relationship between the temperature, RH, and equilibrium moisture content (EMC) at the measurement point. When the moisture content was below the FSP, the calculated MC was slightly greater than the value given by oven drying. The absolute error was within 0.8% near the open cross side, and was within 1.8% at another measurement point. Thus, we concluded that it was practicable to monitor the moisture content below the FSP according to the temperature and pressure inside the wood.

**Key words** Moisture content · Pressure in wood · Relative humidity · RF/vacuum drying · Temperature in wood

## Introduction

Fast drying of wood can be achieved by either a sharp drying schedule such as high-temperature drying or using special drying methods such as radio frequency (RF)/vacuum. In order to make an appropriate drying schedule that will guarantee drying speed and quality of wood products, decrease the drying energy, and analyze the mechanism of drying, it is necessary to know the moisture content distribution in wood during drying. There are many methods for the precise measurement of moisture content before and after drying. However, it is very difficult to measure the moisture content during RF/vacuum drying, because we cannot use metal under an electric field.

Koumoutsakos et al.[1] monitored the total average moisture content by measuring the water level in the collection tank during RF/vacuum drying. However, according to this method some uncondensed vapor from the specimens could be pumped out of the drying chamber, and moisture content distribution cannot be monitored. Therefore, in this study, we focused our attention on developing a monitoring system of moisture content distribution in wood during RF/vacuum drying.

This study was designed to obtain the moisture content from ordinary information such as temperature and pressure. During RF/vacuum drying, the pressure inside the wood is greater than that outside. Thus, the outside air cannot penetrate the wood. The pressure in the wood can be maintained only by water vapor. That is, the wood is filled by saturated vapor when the temperature is lower than the saturated vapor temperature (boiling point), while the vapor is superheated steam when the temperature is higher than the boiling point. The pressure inside the wood is equal to the vapor pressure $p$ and the relative humidity (RH) inside the wood $\phi$ is equal to the ratio of the inside pressure $p$ and the saturated vapor pressure $p_s$, i.e., $\phi = 100p/p_s$. Therefore, the moisture content in wood during drying can be calculated based on the relationship between the equilibrium moisture content (EMC), temperature, and RH. The presence of free water during RF/vacuum drying can be determined based on the relationship between the temperature and pressure inside the wood.[2] Based on the above considerations, the moisture content distribution below the fiber saturation point (FSP) in wood during RF/vacuum drying was monitored.

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Part of this study was presented at the 15th Annual Meeting of the Chugoku Shikoku Branch of the Japan Wood Research Society, Higashi-Hiroshima, Japan, September 2003

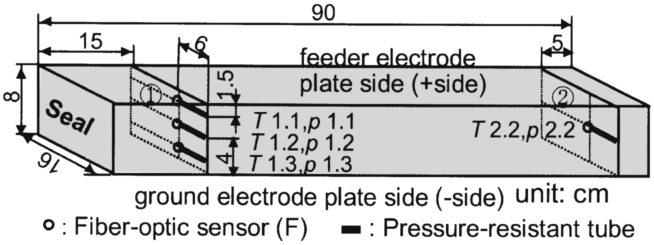


**Fig. 1.** Specimen and points for measurement of temperature and pressure. ①, ②, Sections for measurement of temperature, pressure, and moisture content (MC). The measurement locations are expressed by two numbers. The first number indicates the section in the longitudinal direction. The second indicates the position in the direction of power flow. Temperature was controlled at 1.2

## Materials and methods

### Specimens

*Cryptomeria japonica* D.Don was used as the experimental material. Specimens with dimensions of 17.5 cm (box-heart square timber) × 110 cm (L) were divided into two through the pith, then were processed into specimens with dimensions of 16 × 8 × 90 cm. One cross side was sealed by epoxy resin adhesive. The length corresponded to twice that of the original. One specimen was dried in each run, and four runs were repeatedly done under the following conditions.

### Drying conditions

The RF generator operated at a fixed frequency of 27 MHz, and had a rated output of 1 kW at an electrode RF voltage of 1 kV. The temperature $T_{1.2}$, measured at location 1.2 of the specimen (see Fig. 1), was controlled at about 70°C. The pressure in the chamber was maintained at about 17.9 kPa. The radio-frequency (RF) load was controlled by temperature and time, with the latter having priority. Temperature control meant that the RF load was stopped when $T_{1.2}$ reached 71°C, and the load was resumed when $T_{1.2}$ was lower than 69°C. The time control was set to be a 9-min RF load and a 1-min unload of RF throughout the entire drying process.

### Measurement method

#### *Apparatus*

A sensor complex for simultaneously measuring temperature and pressure at the same point was developed (Fig. 2) as described by Cai and Hayashi.[2] The connecting pressure-resistant tube conducting the pressure in the specimen was filled with oil to prevent the state change and pressure reduction of transmission media by ambient temperature. Because cavitation in oil should be avoided, and the area between the joint and the pressure-resistant tube must be airtight, we took the following steps: we selected a pressure-resistant tube with a small internal diameter and an airtight joint between the tube and the sensor; we sealed the joint with high-strength adhesive; and we developed a new vapor-tight measurement device. We measured temperature and pressure at four locations (Fig. 1) at 3-min intervals during the drying process using this measurement device.

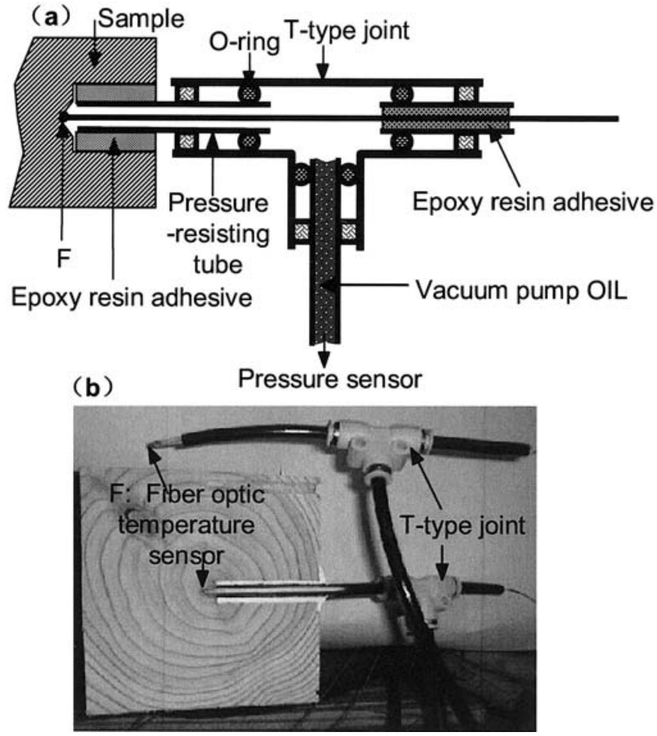


**Fig. 2a,b.** Schematic diagram indicating the measurement of temperature and pressure within the sample. **a** Schematic design, **b** actual picture

#### *Calculation of the moisture content*

Relative humidity (RH) was calculated as

$$\phi = p/p_s \times 100(\%) \qquad (1)$$

where $\phi$ is RH, $p_s$ is saturated vapor pressure corresponding to the measured temperature, and $p$ was the partial vapor pressure that was assumed to be equal to the measured pressure in the specimen in a vacuum condition.

The EMC mainly depended on RH and ambient temperature. Temperature and pressure were measured at 3-min intervals during the drying process, and then were averaged at 30-min intervals. The RH ($\phi$) was calculated according to Eq. 2.

$$\phi = \frac{\overline{p}}{\overline{p_s}} \times 100(\%) \qquad (2)$$

where $\overline{p}$ is the mean pressure measured in the specimen, and $\overline{p_s}$ is saturated vapor pressure corresponding to the mean temperature measured in the specimen.

The moisture content at the same location was estimated by Keylwerth's EMC chart.[3]

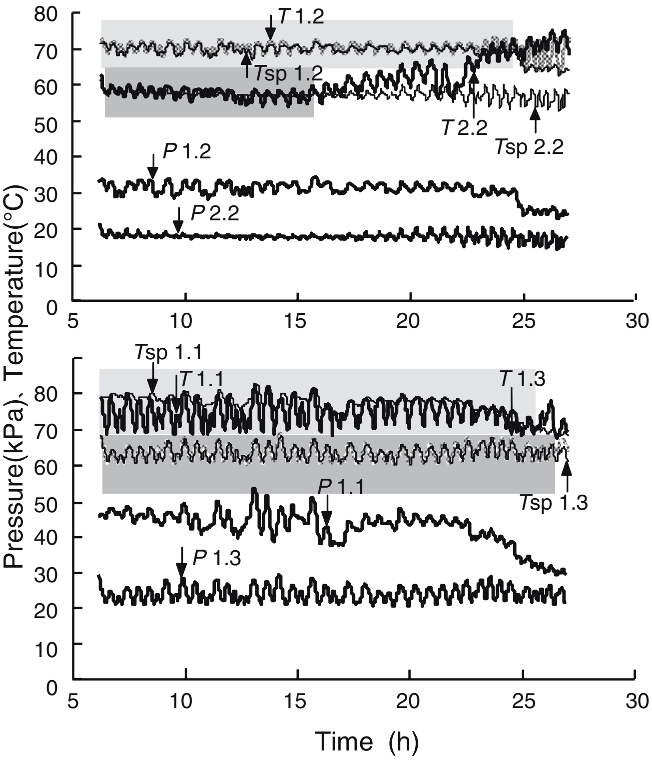


Fig. 3. Changes in the pressure and temperature in the specimen during radio-frequency (RF)/vacuum drying in run 1. $T_{sp}$ represents the saturation temperature (boiling point) at the measured pressure

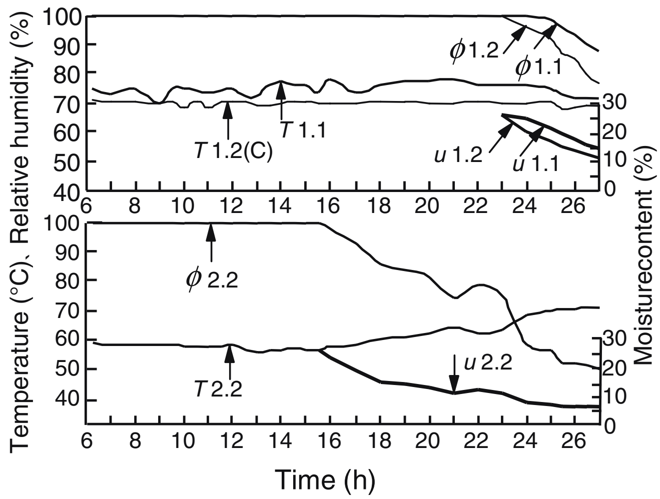


Fig. 4. Changes in the temperature ($T$), relative humidity ($\varphi$), and estimated moisture content ($u$) during RF/vacuum drying in run 1

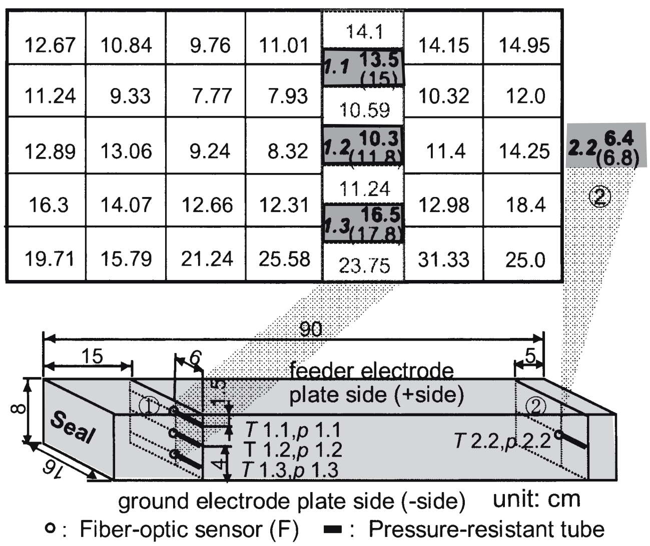


Fig. 5. The moisture content distribution at profiles ① and ② after drying in run 1, given as percentages. The value in the parenthesis is estimated, the other is determined by the oven-drying method

## Results and discussion

### Variation of temperature and pressure inside the wood during RF/vacuum drying

Figure 3 shows the changes in temperature and pressure at four locations in the specimen with time in run 1. $T_{sp}$ represents the saturation temperature (boiling point) for the pressure measured at the same location. The shaded areas show the process for when the specimen temperature did not surpass the boiling point. That is, the temperature inside the wood was equal to the boiling point at the measured pressure when was free water was present. The temperature in the wood was higher than its boiling point when no free water was present.[2] According to this estimation, the shaded areas represent the existence of free water for each measurement point during the drying process. The moisture content of the period without shading was below the FSP. The elapsed time for the loss of free water was different for each location. For example, the fastest drying location was near the open cross side (location 2.2 in Fig. 1) where the free water was removed after 16h of drying; next was location 1.2, near the center of the specimen, where free water was removed after 23h; location 1.1 near the feeder electrode plate was dried after 25h; and location 1.3 near the ground electrode plate was dried after about 26h. Similar results were observed in three other runs.

### Change in moisture content

The changes over time in mean measured pressure, temperature, RH calculated by Eq. 2, and the estimated moisture content ($u$) below FSP at each location in run 1 are shown in Fig. 4. The moisture content distributions of cross sections ① and ② were obtained by the oven-drying method after RF/vacuum drying and compared with the estimated moisture content in Fig. 5 (run 1).

The estimated moisture contents at test locations 1.1, 1.2, 1.3, and 2.2 were 15%, 11.8%, 17.8%, and 6.8%, respectively, and those determined by oven drying were 13.5%,

**Table 1.** Absolute errors of the moisture content estimated in run 1

| Measurement location[a] | Absolute error[b] (%) |
|---|---|
| 1.1 | 1.5 |
| 1.2 | 1.5 |
| 1.3 | 1.3 |
| 2.2 | 0.4 |

[a] Measurement locations are defined in Fig. 1
[b] Absolute error = estimated moisture content – moisture content determined by the oven drying method

**Table 2.** Maximum absolute errors of the moisture content estimated at each location in four runs

| Measurement location error (%) | Maximum absolute |
|---|---|
| 1.1 | 1.6 |
| 1.2 | 1.5 |
| 1.3 | 1.8 |
| 2.2 | 0.8 |

10.3%, 16.5%, and 6.4%, respectively. The estimated values were slightly higher than those obtained by the oven-drying method. Tables 1 and 2 show the errors at each location in run 1 and maximum errors for the four runs, respectively.

While these errors are acceptable, they may have been caused by a system error that could be remedied by revision of the EMC chart, which was calculated without considering the effect of species, pressure of the surrounding vapor, or the drying conditions. Consideration should also be given to the fact that it may take some time to reach the EMC.

The system error from the measurement of the pressure in the samples could be addressed. Therefore, we conclude that it was practicable to monitor the moisture content below the FSP based on the temperature and pressure inside the wood.

## Conclusions

Temperature and pressure inside the wood were measured during the process of RF/vacuum drying. RH and the moisture content in the wood were calculated. The practicability of monitoring the moisture content based on the temperature and pressure inside the wood was investigated. The results were as follows:

1. The moisture content could not be estimated at locations where free water existed because the relative humidity was always 100%.
2. The estimated moisture contents were higher than those determined by the oven-drying method within 1.8% at the measurement point except near the open cross side.
3. It was considered acceptable to monitor the moisture content below the FSP by recording the temperature and pressure inside the wood in a practical drying run.

**Acknowledgments** We thank the Yasujima Company for their assistance. This work was supported by Project no. 30571453 from the Chinese National Natural Science Fund and by the program of the Ministry of Education no. JJSI[2003] 406 and no. JKJS 106066.

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