EFFECT OF AMBIENT PRESSURE ON EQUILIBRIUM MOISTURE CONTENT OF WOOD

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Abstract. The equilibrium moisture content (EMC) of Russian larch wood, Sugi wood, and Hinoki wood was measured under vacuum conditions at temperatures of 45, 50, and 60°C and ambient pressures of 13.3, 53.3, and 101.3 kPa. The results show that the EMC of each species increased with a decrease in ambient pressure. The effect of temperature and RH on EMC under vacuum conditions showed a similar tendency. Wet-bulb temperature needed to be controlled to measure EMC, even under vacuum, because pressure was not maintained only by water vapor pressure because of the presence of air in the vessel. There were obvious differences between the EMC values obtained in this experiment and previous experimental EMC values in which the wet-bulb temperature was not controlled.

Keywords: Equilibrium moisture content (EMC), ambient pressure, vacuum drying, wet-bulb temperature.

INTRODUCTION

The moisture content of wood in equilibrium under constant temperature and RH is termed equilibrium moisture content (EMC). Although RH and temperature are the principal factors that determine EMC, it is also affected by sorption processes, mechanical stress, species, and extractive content (Skaar 1988). EMC under atmospheric pressure has been presented in a unified description by Kollmann (1968) and serves well in wood research and wood manufacturing, especially in conventional wood drying. In the last decade, vacuum drying as a rapid drying method (Simpson 1987) has been steadily increasing for valuable species and

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those prone to collapse from the relatively higher temperatures in conventional wood drying and is likely to continue increasing in the future. For vacuum drying, EMC conditions still need to be controlled to perform the drying run (Chen and Fred 2002). However, few data on EMC for vacuum drying have been reported in the literature. Although EMC under vacuum was reported by Chen and Fred (2002) and Yi et al (2008) based on the assumption that there is no air present in the chamber during vacuum drying, the results obtained showed obvious differences from Kollmann's EMC as well as each other. Furthermore, the graph they derived was the relationship among temperature, ambient pressure, and EMC rather than the relationship among temperature, ambient pressure, RH, and EMC. Hence, only Kollmann's EMC can be used for moisture content monitoring under radiofrequency/vacuum drying based on a new concept (Cai and Hayashi 2007) using detected temperature and pressure in wood. Therefore, with the development of vacuum drying procedures, EMC data with sufficient accuracy under vacuum condition are more important for wood vacuum drying in theory and practice.

Although it was assumed that there was no air in the chamber during vacuum drying in the research by Chen and Fred and Yi et al, some air does, in fact, enter the chamber, resulting in total pressure differing from partial vapor pressure. The condition of the chamber under vacuum is also governed by temperature and RH as atmospheric conditions. The definition of RH under vacuum is the same as that under atmospheric conditions, which is the ratio of the partial vapor pressure to the saturated pressure for a given temperature (Siau 1995). Xiao and Cai (2009) investigated the factors affecting RH during wood vacuum drying and found that RH was affected slightly by ambient pressure. Effects on RH by ambient pressure can also be found in equations for RH calculations. Hence, to maintain correct RH, ambient pressure must be considered as indicated by the equations. Generally speaking, from the isothermal process, RH decreases with decreasing pressure based on the premise that pressure is maintained only by water vapor. In fact, there is air in the chamber as explained previously in this article. For a certain ambient pressure of the chamber, RH depends on the extent of water vapor pressure and not on total pressure. Because the evaporation of water in wood is governed by temperature and humidity, RH as well as temperature must be considered to determine EMC of wood even under vacuum conditions. Therefore, in this study, the objective was to investigate the effect on EMC of ambient pressure while maintaining a constant RH throughout the test by adjusting the wet-bulb temperature and to establish the relationship among EMC, temperature, RH, and ambient pressure based on three softwoods under various ambient pressure conditions.

MATERIALS AND METHODS

Materials

Materials used were Russian larch (*Larix gmelinii,* 510 kg/m^3 basic density, 48% initial MC), Hinoki (*Chamecyparis obtusa,* 400 kg/m^3 basic density, 37% initial MC), and Sugi (*Cryptomeria japonica,* 320 kg/m^3 basic density, 90% initial MC). Each species was processed into 25 end-matched EMC test samples with dimensions of 5 (L) $\times$ 30 (T) $\times$ 30 (R) mm.

Methods

As shown in Table 1, the temperature ranges and ambient pressure ranges were 45, 50, and 60°C and 13.3, 53.3, and 101.3 kPa, respectively. For each condition, the temperature and RH were held constant throughout the test. Intermediate mass within a 3-da interval was measured in every pressure condition and the specimens were considered at EMC while the mass difference was within 2 mg between the last two intervals. First, five samples of each species were subjected to an ambient pressure of 13.3 kPa until all the samples reached EMC at this pressure. After the samples were weighed, the ambient pressure was changed to and held at 53.3 kPa until all the

Table 1. Equilibrium moisture content test conditions, controlling parameters, and calculated RH under various ambient pressures.

Test conditions			Controlling parameters			Calculated RH
t (°C)	RH (%)	Pressure (kPa)	t_w (°C)	P_s (kPa)	P_w (kPa)	Φ (%)
45	60	13.3	35.6	9.535	5.779	60.1
		53.3	36.3	9.535	6.009	60.1
		101.3	37.0	9.535	6.247	60.1
45	50	13.3	32.4	9.535	4.827	49.9
		53.3	33.5	9.535	5.135	50.0
		101.3	34.5	9.535	5.433	49.9
50	60	13.3	40.1	12.221	7.398	60.2
		53.3	40.7	12.221	7.639	60.2
		101.3	41.3	12.221	7.885	60.1
50	40	13.3	33.0	12.221	4.993	40.1
		53.3	34.4	12.221	5.402	40.1
		101.3	35.7	12.221	5.811	40.1
60	50	13.3	45.9	19.841	9.969	50.1
		53.3	46.5	19.841	10.324	50.1
		101.3	47.3	19.841	10.723	50.1

t, dry-bulb temperature; RH, designed RH; t_w, wet-bulb temperature; P_s, saturated vapor pressure at the dry-bulb temperature; P_w, saturated vapor pressure at the wet-bulb temperature; Φ, calculated RH by Eq 3.

samples again reached EMC. After the samples were reweighed, the pressure was changed to and held at 101.3 kPa until all the samples reached EMC under atmospheric pressure. Finally, after weighing, all the samples were dried in the oven at 103 ± 2°C for 24 h.

The pressure inside the chamber was measured with a diaphragm pressure gauge. The pressure was maintained to within ±0.26 kPa of the controlling value by the vacuum pump. The internal RH was controlled using dry- and wet-bulb temperatures. To control the wet-bulb temperature, the chamber was equipped with a steam generator, condenser, and cooling pipe, and an air circulation fan was used to equalize the temperature and humidity. A variable-frequency motor was used to ensure the airflow velocity over the wet-bulb probe was over 1 m/s at various ambient pressure conditions.

RH Calculation for Vacuum Conditions

Three equations were used to calculate RH under vacuum conditions (JSME 1959; Carpenter 1982; Yan and Wang 2004). The calculated values using these equations were almost the same, therefore, the simplest, Eq 3, was chosen for the RH calculation. The equations show that RH is affected by ambient pressure, therefore, to control the designed test conditions, the wet-bulb temperature was adjusted as shown in Table 1. For example, to obtain the condition of 45°C and 60% RH under pressures of 13.3 kPa, 53.3 kPa, and 101.3 kPa, the wet-bulb temperature should be adjusted from 35.6 to 36.3°C and then to 37.0°C, respectively.

$$\phi 1 = \frac{0.001P_w - k\dfrac{0.001P}{755}(t - t_w)}{0.001P_s} \times 100\% \quad (1)$$

$$\phi 2 = \frac{100P(A_w - D)}{(AP - (A - A_w + D)P_s)} \times 100\% \quad (2)$$

$$A = \left(1555.6 - 1.151t + 0.00013t^2 - 2.604t_w\right)\frac{P_s}{P - P_s}$$

$$A_w = \left(1555.6 - 1.453t_w + 0.00013t_w^2\right)\frac{P_{s(t_w)}}{P - P_{s(t_w)}}$$

$$D = 1.002(t - t_w) + 0.00005\left(t^2 - t_w^2\right)$$

$$P_{s(t\succ 0°c)} = 0.022064\exp\left\{\left[\begin{array}{l}7.2148 + 3.9564\left(0.745 - \dfrac{t + 273.15}{647.14}\right)^2 \\ + 1.3487\left(0.745 - \dfrac{t + 273.15}{647.14}\right)^{3.1778}\end{array}\right]\left(1 - \frac{647.14}{t + 273.15}\right)\right\}$$

$$\phi 3 = \frac{P_w - \dfrac{(P - P_w)(t - t_w)}{1546 - 1.44t_w}}{P_s} \times 100\% \quad (3)$$

where φ is RH (%), P_w is saturated vapor pressure at the wet-bulb temperature (kPa), P is ambient pressure (kPa), t is dry-bulb temperature (°C), t_w is wet-bulb temperature (°C), P_s is saturated vapor pressure at the dry-bulb temperature (kPa), and k is the air coefficient with a value of 0.6 under vacuum.

Apparatus

The vacuum chamber with an inside dimension of 0.8 × 0.8 × 1.1 m (Yashijima Co, Ltd) shown in Fig 1 was used for the EMC test under vacuum conditions and consists mainly of a pressure control system, steam generator, and online monitoring system for dry- and wet-bulb temperature measurement. The performance of this vacuum chamber such as precise dry- and wet-bulb temperature measurement, wind velocity adjustment under different vacuum conditions, etc, was tested by Myojin et al (2006) and fully met the requirements of the experiment. An electronic balance (METTLER AJ100) with a precision of 0.1 mg was used to measure the weight of EMC samples.

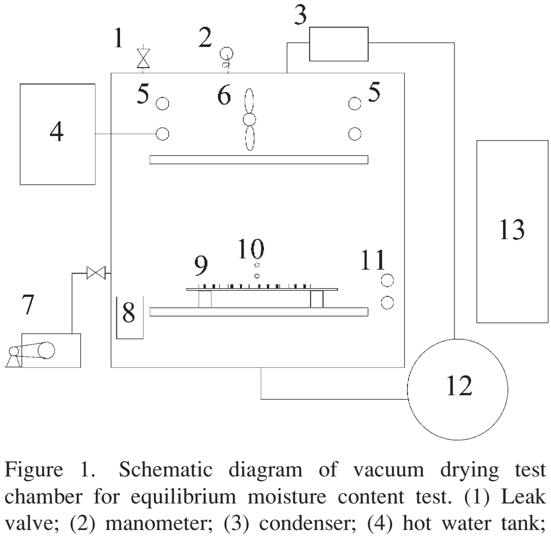

Figure 1. Schematic diagram of vacuum drying test chamber for equilibrium moisture content test. (1) Leak valve; (2) manometer; (3) condenser; (4) hot water tank; (5) heating pipe; (6) circulating fan; (7) vacuum pump; (8) steam generator (9); samples; (10) dry- and wet-bulb temperature sensors; (11) dehumidifier; (12) water collector; (13) control cabinet.

RESULTS AND DISCUSSION

EMC of Wood Under Vacuum Conditions

The EMC values of Larch, Hinoki, and Sugi under various vacuum conditions are presented in Table 2 and Fig 2 to show the observed trends. Figure 2 clearly shows that the effect of ambient pressure on EMC for the three species was similar under the same temperature and RH conditions. That is, EMC increased with a decrease in ambient pressure. Table 2 shows that the difference in EMC between 13.3 and 53.3 kPa was between 1.2 and 1.9%, while the difference in EMC between 53.3 and 101.3 kPa was only 0.1-0.4%. This shows that the extent of the effects was significant at low ambient pressure (13.3 kPa) compared with the effects at medium ambient pressure (53.3 kPa), and ambient pressure is one of the factors affecting EMC in addition to temperature and RH. On the other hand, EMC of the three species in Table 2 at atmospheric pressure (101.3 kPa) for various temperatures and RH was different from the value in Kollmann's EMC chart for Sitka spruce, which shows EMC is affected by species as mentioned before.

EMC at atmospheric pressure increases with increasing RH and decreases with increasing

Table 2. Equilibrium moisture content of Russian larch, Hinoki, and Sugi under various conditions.[a]

		Temperature (°C)/RH (%)				
Species	Pressure (kPa)	45/60	45/50	50/60	50/40	60/50
Russian Larch	13.3	11.6	10.3	10.8	8.6	9.2
	53.3	9.7	8.7	9.3	6.8	7.5
	101.3	9.6	8.6	9.0	6.4	7.1
Hinoki	13.3	10.5	9.9	10.2	7.2	8.7
	53.3	8.9	8.2	8.7	6.0	7.0
	101.3	8.8	8.0	8.6	5.7	6.5
Sugi	13.3	10.1	9.2	9.8	7.5	8.5
	53.3	8.9	8.0	8.6	6.2	7.1
	101.3	8.6	7.6	8.5	5.8	6.5
Kollmann	101.3	9.7	8.2	9.5	6.5	7.3

[a] Kollmann's equilibrium moisture content was for Sitka spruce.

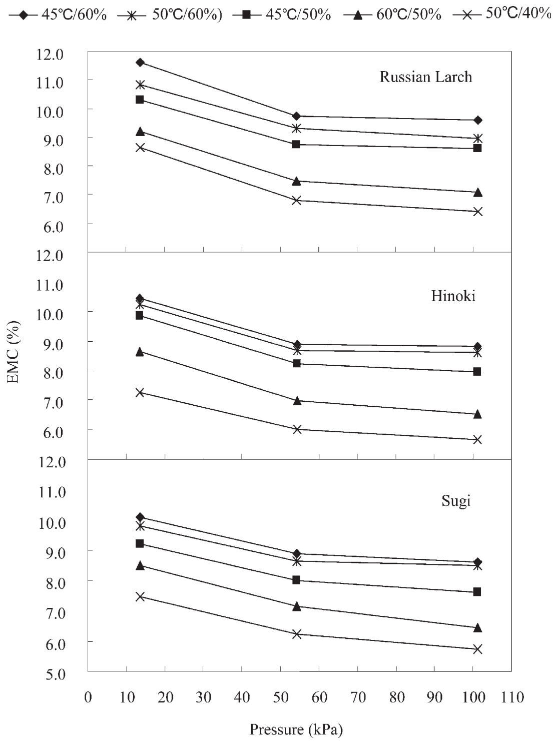

Figure 2. Equilibrium moisture content of Russian larch, Hinoki, and Sugi wood for various conditions under vacuum.

temperature (Skaar 1988). Figure 2 and Table 2 show that, under vacuum and at any ambient pressure, EMC has the same tendency for all three species. That is, at the same temperature for a given ambient pressure, EMC increased with an increase in RH, and at the same RH for a given ambient pressure, EMC decreased with an increase in temperature. The degree of effect was not significant at the three ambient pressures.

Comparison of EMC to Previous Research

A comparison of the EMC obtained by Yi et al (2008) to the EMC determined for Russian larch wood, Hinoki, and Sugi in this experiment shows differences between the two sets of pressure values (see Fig 3). The EMC obtained by Yi et al increased with an increase in ambient pressure—even EMC in this experiment differed between species at any given ambient

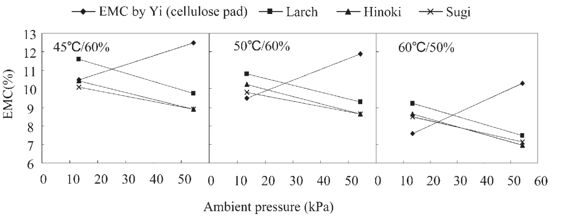

Figure 3. Comparison of equilibrium moisture content of Russian larch, Hinoki, and Sugi wood to previous research under vacuum conditions.

pressure—while the EMC in this experiment decreased with an increase in ambient pressure for all three species at a constant temperature and RH. The discrepancies at low ambient pressure (13.3 kPa) were not significant for two reasons: species and actual RH. The material used by Yi et al was a wafer (a cellulose pad) which is different from wood fibers but resulted in similar EMC to wood species, for which the differences can be attributed to species effects. In Yi et al's test, the RH inside the chamber was not controlled, and in fact, the RH at this pressure level was close to the RH controlled in the present experiment, which resulted in the EMC in their test being similar to the EMC of the three species in this experiment. The discrepancies at medium ambient pressure (53.3 kPa) were significant, which can be attributed mainly to RH effects and not species because no significant effects result from differences in species. These differences can be explained by the differences in RH at this pressure level in the two experiments. For example, for 60°C/50% RH (see Fig 3) in this experiment, the temperature and RH were kept constant at 60°C/50% RH at all ambient pressures; in Yi et al's test, temperature was maintained at 60°C but the RH was not controlled at the corresponding ambient pressures because their test was based on the assumption that pressure in a vacuum was maintained only by water vapor. At 53.3 kPa, the RH in Yi et al's test was 100%, but the actual RH was lower than that because of air being present in the chamber. However, the RH was estimated to be much greater than 50%, resulting in a higher EMC compared with this experiment. For other conditions, the significant discrepancies at 53.3 kPa were also because of the same reason for the differences in RH at the same temperature and ambient pressure. In Yi et al's test, the actual RH increased with an increase in ambient pressure. Therefore, RH should be controlled to determine EMC even under vacuum conditions.

CONCLUSIONS

EMC of Russian larch, Hinoki, and Sugi at three temperature levels was measured under various vacuum conditions with the following conclusions:

1. Ambient pressure was one factor affecting EMC. EMC increased more than at atmospheric pressure for the three species with a decreasing ambient pressure. It became clear that wet-bulb temperature needs to be controlled to measure EMC, even under vacuum, because pressure was not only maintained by water vapor pressure, but also from air entering the vessel.
2. The effect of temperature and RH on EMC under vacuum conditions showed a similar tendency to the effect of temperature on EMC under atmospheric pressure in that EMC increased with a decrease in temperature and increased with an increase in RH at any ambient pressure.
3. There were obvious differences between EMC values based on the assumption that pressure under vacuum is maintained only by water vapor and the EMC values in this experiment, because EMC was obtained for different RH under the same ambient pressure.

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