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ORIGINAL ARTICLE

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In situ measurement of wood moisture content in high-temperature steam

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Abstract Changes in moisture content of sugi (*Cryptomeria japonica* D. Don) wood during high-temperature saturated and superheated steam treatments were investigated. A system for in situ weighing of specimens was used, and the reduction of wood substance by heating was taken into consideration. At 160°C the loss of wood substance due to heating was significant and influenced the moisture content values, but it was almost negligible at 120°C. Treatment time and temperature affected the moisture content in saturated steam but not in superheated steam. Excess water in a saturated closed system appears to promote the decomposition of wood and condensation in or on specimens.

Key words Moisture content · Saturated and superheated steam · In situ measurement · Loss of wood substance

Introduction

High-temperature and high-pressure steam is now being applied to wood drying, board production processes, and other uses. Steam treatments are known to have several beneficial effects, such as removing wood moisture and heavy resins,[1] improving permeability,[1–3] reducing the drying time and growth stress,[4–9] and stabilizing dimensions.[10] The treatments, however, also have some side effects, such as discoloration, reduction of strength, and promotion of erosion inside kilns due to the generation of organic acids.[2,11] These changes in wood by steaming are closely related to the wood moisture content as well as treating conditions. Therefore, it is important to know the wood moisture content in various steam atmospheres to elucidate the influence of steaming on wood and to find the optimum treatment conditions by which defects can be avoided.

Equilibrium moisture content of wood in high-temperature and high-pressure steam has mainly been estimated by two methods: extrapolation of low-temperature data to higher temperatures and actual experiments.[12–14] The equilibrium moisture content values reported are significantly diverse at regions of high relative humidity. This is probably due not only to the difficulty of evaluating the moisture content in a closed system but also to differences in conditions for obtaining the data. In this study, therefore, the effect of treatment conditions on wood moisture content in high-temperature and high-pressure steam was investigated using a system for in-situ weighing of a specimen under treatment.

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Materials and methods

Specimens

Sapwood and heartwood specimens of sugi (*Cryptomeria japonica* D. Don) with dimensions of 30 (T) × 20 (R) × 2 (L) mm were used. The specimens were so thin that each wood fiber could be easily exposed to the atmosphere. Before and after each steam treatment, specimens were dried and then weighed to determine the weight of wood substance for each specimen. The drying was conducted over P_2O_5 in a vacuumed desiccator to avoid the influence of heating on the specimens.

In situ measurement of specimen weight

Changes in specimen weight during high-temperature steam treatment were measured with the closed system shown in Fig. 1. The in situ change in weight of a sample suspended by a helical quartz spring in a pressure-tolerant glass reactor was measured with a cathetometer as described by Lee et al.[15]

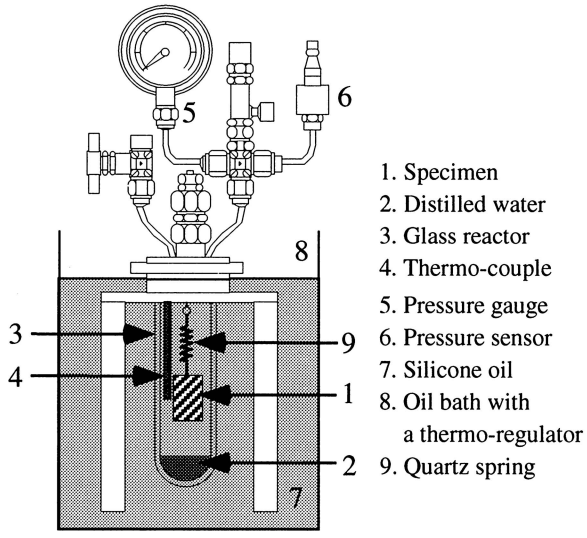

Fig. 1. System for in situ wood moisture measurement at elevated temperatures and pressures

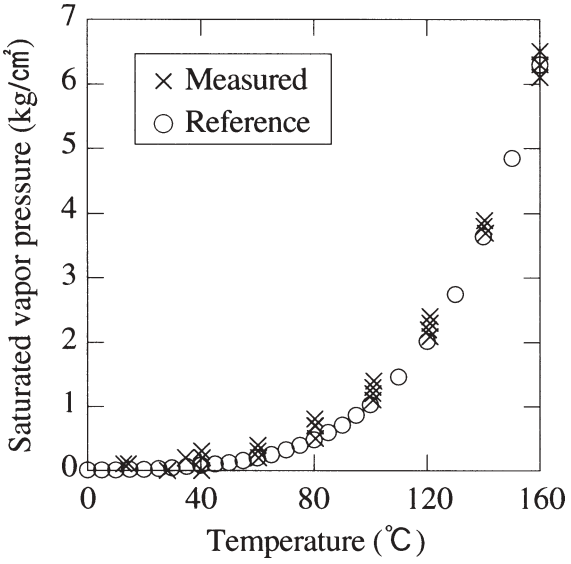

Fig. 2. Comparison of measured and reference values for saturated vapor pressure

The pressure gauge and piping, which could not be immersed in high-temperature oil, were covered with band heaters and adjusted to the same temperature as that of the oil bath using a temperature controller (SU10N1120-LFNNS; Chino Co. Japan) to prevent condensation in the piping and the glass reactor.

Treatment conditions

Vapor pressure was controlled by the amount of distilled water put in the reactor. Because air could not be fully evacuated from the reactor, the pressure gauge showed the combined pressure of both vapor and air in the reactor. In this study the measured pressure of the reactor in which water remained was regarded as saturated pressure. Figure 2 compares the measured and reference values for saturated vapor pressure. The relative vapor pressure inside the reactor (RV) was calculated as follows.

$$\mathrm{RV} = (p_v + p_a)/(p_{vs} + p_a) = p_m/p_{ms}$$

where p_v and p_a are the partial pressures of the vapor and the air in the reactor, p_{vs} is the saturated vapor pressure, p_m is the measured pressure inside the reactor, and p_{ms} is the measured saturated pressure.

Loss of wood substance by steam treatment

To calculate the moisture content of wood under steam treatment, changes in the weight of wood substance during the treatment were measured. Matched specimens were treated under several relative vapor pressures, temperatures, and treatment times with the system shown in Fig. 1. The weight loss of wood substance (w_{ls}) was then calculated as

$$w_{ls}(\%) = (w_{0i} - w_0)/w_{0i} \times 100$$

where w_{0i} and w_0 are the weight of wood substance before and after steam treatment, respectively. The weight of wood substance was represented by the weight of specimens dried over P_2O_5 in a vacuum desiccator.

Cold-water and hexane extraction

Steam-treated samples were air-dried, cut into pieces, and ground in a mill to pass through an 80-mesh screen. The ground samples in 1-g units were Soxhlet-extracted with *n*-hexane at 85°C for 6 h. The solvents were evaporated in vacuo at room temperature. Other 1-g ground samples were extracted with 150 ml of distilled water in flasks at room temperature for 48 h with occasional stirring. The solvents were filtered with distilled water using glass filters and then oven-dried at 105°C until their weights stabilized.

Results and discussion

Apparent moisture content and moisture content

Figure 3 shows the relation between the treatment time and the weight of specimens at several vapor pressures obtained by in situ measurements. The weight of specimens in saturated steam increased with treatment time, whereas it slightly decreased or was almost unchanged in superheated steam. Using these data, the apparent moisture content (AMC), which does not consider the weight loss of wood substance by heat, can be calculated as

$$\mathrm{AMC}(\%) = (w_s - w_{0i})/w_{0i} \times 100$$

where w_s is the weight of the specimen under steam atmosphere, and w_{0i} is the initial weight of the wood substance. The results are plotted in Fig. 4.

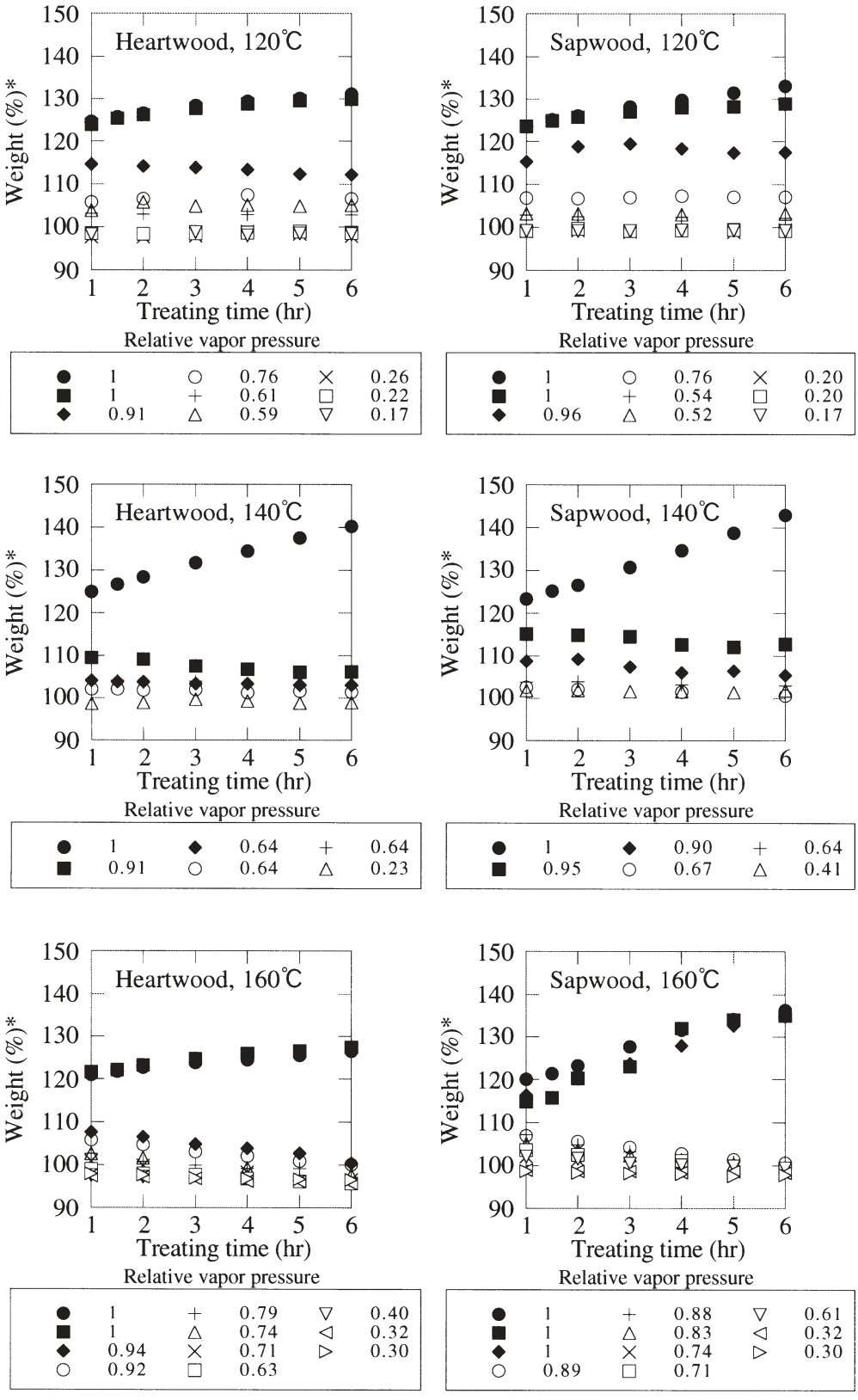

Fig. 3. Changes in specimen weight at several vapor pressures obtained by in situ measurement. *Weight (%) = $w_s/w_{0i} \times 100$, where w_s is the weight of specimen under steam atmosphere and w_{0i} is the initial weight of the wood substance

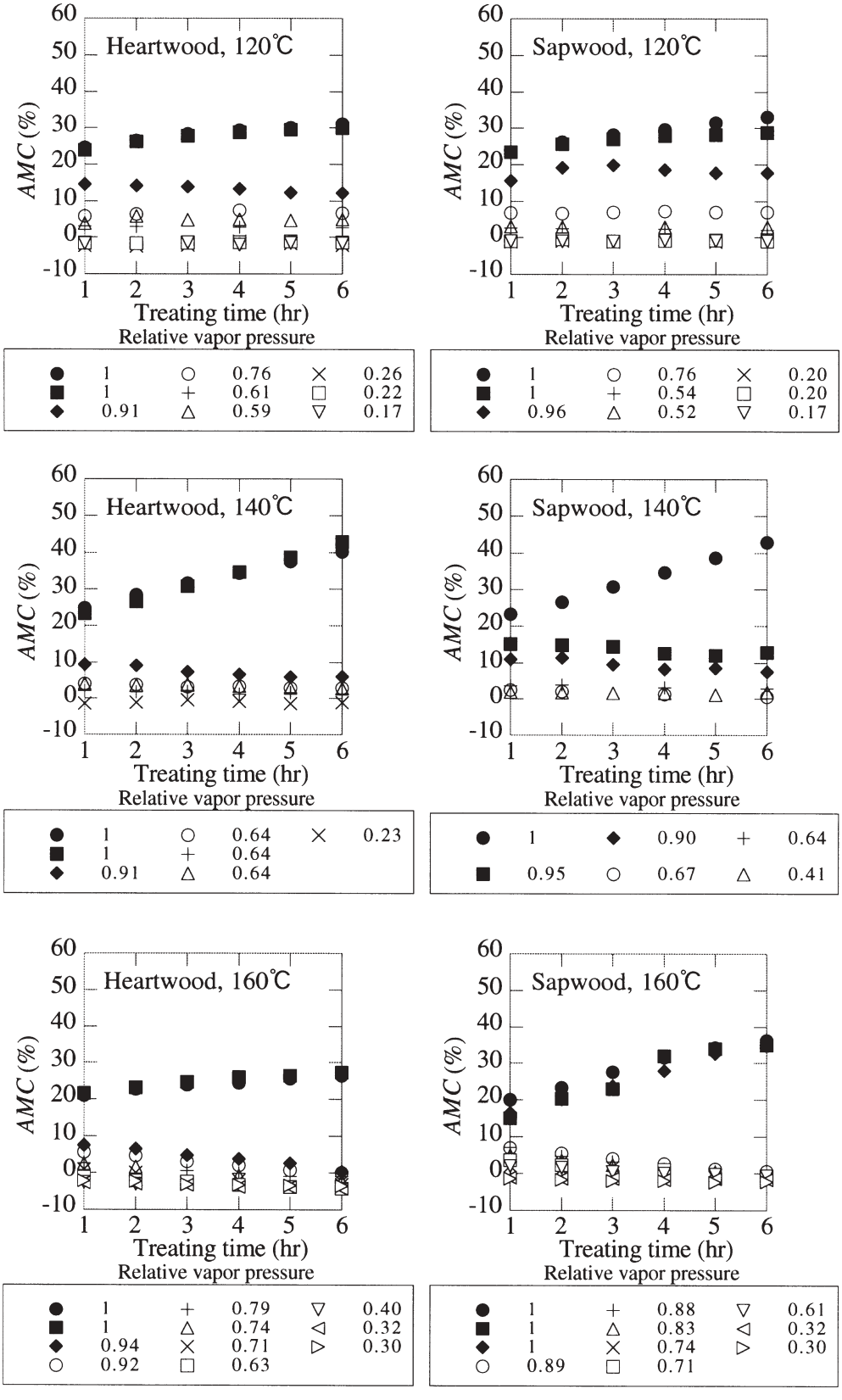

Fig. 4. Apparent moisture content (*AMC*) of specimens under several vapor pressures

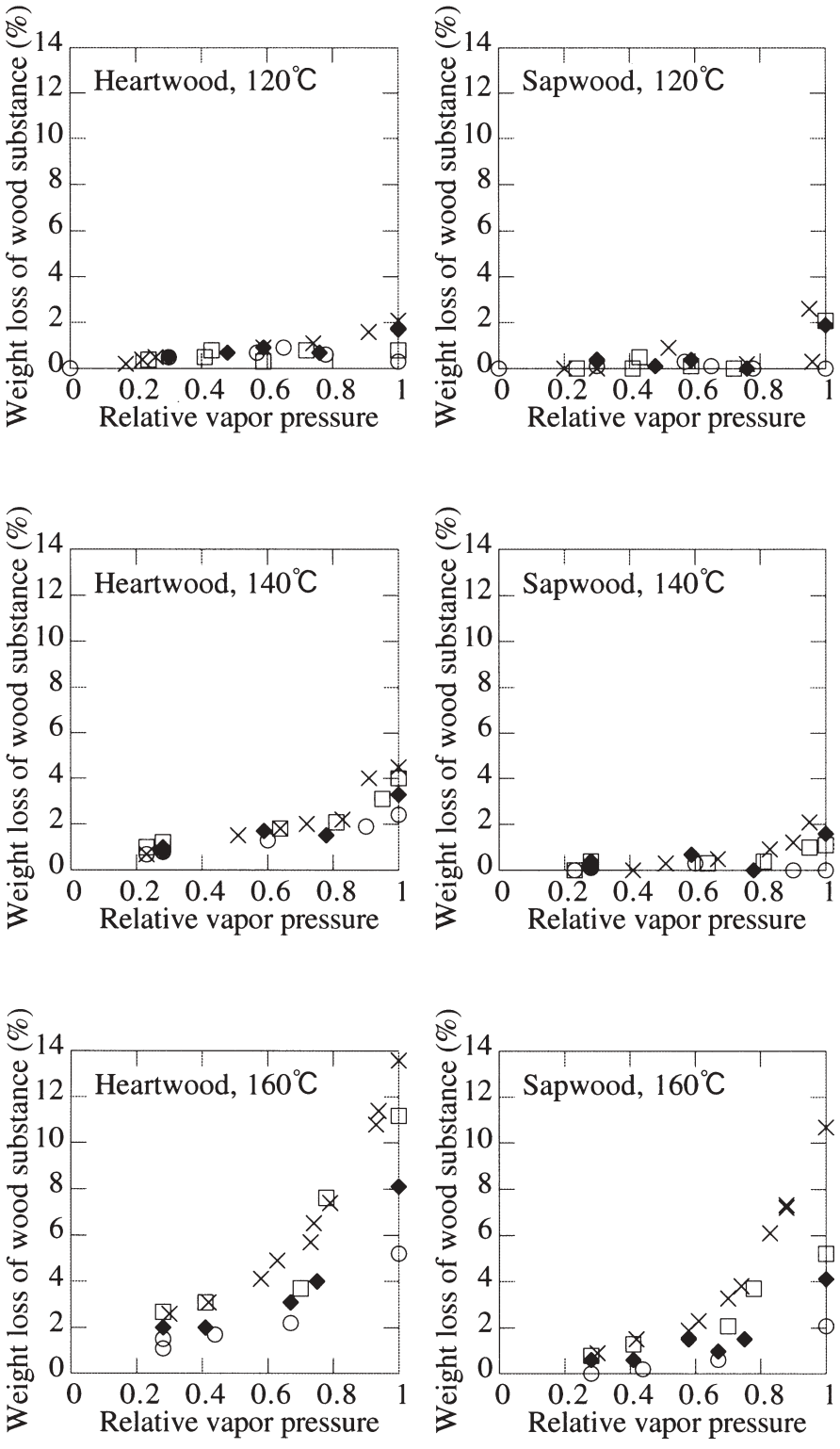

Fig. 5. Weight loss of wood substance (w_{ls})* by steam treatments. Treatment times: *circles*, 1 h; *diamonds*, 2 h; *squares*, 4 h; ×6 h. *w_{ls} (%) = $(w_{0i} - w_0)/w_{0i} \times 100$, where w_{0i} and w_0 are the weights of the wood substance before and after steam treatment, respectively

To obtain more accurate moisture content values, the weight loss of wood substance as a function of treatment time, temperature, and vapor pressure was measured and then plotted in Fig. 5. The loss of wood substance became significant as the temperature, vapor pressure, and treatment time increased. The loss of wood substance in heartwood specimens was greater than in sapwood specimens in the regions of high vapor pressure, especially as the temperature increased.

The moisture content values were calculated from the changes in specimen weight shown in Fig. 3 and the weight of the wood substance under the same conditions shown in Fig. 5. The results were plotted in Fig. 6. After comparing these moisture content values with the AMC shown in Fig.

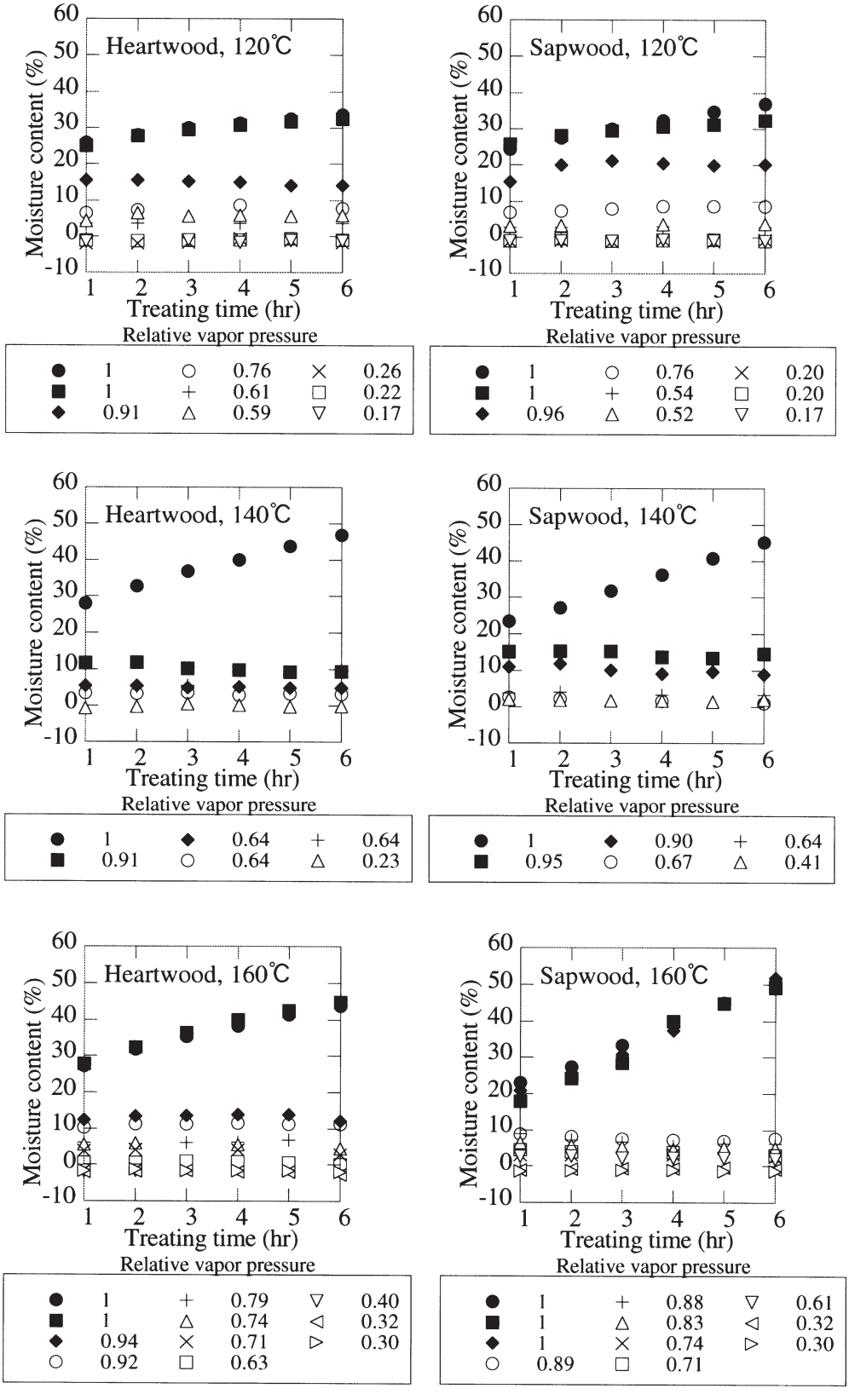

Fig. 6. Changes in moisture content during steam treatments

4, it is evident that the moisture content values became higher than the AMC when taking into consideration the loss of wood substance during treatment.

Influence of treatment conditions on moisture content

As shown in Fig. 6, the moisture content in superheated steam increased with relative vapor pressure but remained almost constant regardless of the treatment time and temperature. On the other hand, in saturated steam the moisture content increased especially at higher temperatures.

The reason for the significant increase in moisture content under saturated steam may have been as follows. Under saturated conditions in this experiment, liquid water always remained at the bottom of the glass reactor. This liquid water vaporized when the vapor in the reactor was absorbed by the wood specimen; then the atmosphere in the reactor would be kept saturated. If condensation and absorption of moisture occurred in a specimen, it is possible that the moisture content of the wood increased consistently with the treatment time until the wood temperature became exactly the same as that of the atmosphere in the reactor.

Chemical and structural changes in wood substances might also have induced high moisture content in saturated steam. The results of both hexane and cold-water extractions of steam-treated specimens are shown in Table 1. The amount of hexane extracts (which mainly consist of terpens[16]) in heartwood specimens was decreased by steam treatment, whereas the amount in sapwood was almost unchanged. The amount of cold-water extracts, which have been reported to consist of water-soluble carbohydrates and glycosides,[16,17] increased in both heartwood and sapwood after steam treatment, especially at high temperatures. Most of the increase in the cold-water extracts was likely caused by the decomposition of hemicellulose.[18,19] It has been reported, in addition, that hemicellulose and lignin in wood are softened under such conditions.[20] If the decrease and softening of the chemical components in wood induce loosening of the intra- and interbonds of the components and increase the number and volume of voids or capillaries in the cell wall, condensation of water becomes more likely to occur and the amount of water absorption should increase. This explanation, however, is merely speculation and should be further examined.

Table 1. Results of hexane and cold-water extractions

Specimen	Hexane extracts (%)	Cold water extracts (%)
Heartwood		
Control	3.1	11.7
Saturated steam-treated (120°C, 6h)	1.8	12.1
Saturated steam-treated (160°C, 6h)	0.8	14.5
Sapwood		
Control	0.4	9.0
Saturated steam-treated (120°C, 6h)	0.4	11.1
Saturated steam-treated (160°C, 6h)	0.6	18.3

Comparison of reported moisture content values

Figure 7 compares the moisture content values reported in the literature. The data obtained for superheated steam in this study were in the same range as the other reported values. Because there was not much loss of wood substance in regions of low relative vapor pressure and the moisture content values are low, there is not much diversity among moisture content values obtained from various sources. For the saturated vapor condition, the data reported by Kauman,[14] Engelhardt,[13] and Strickler[12] are not consistent. The values for moisture content obtained in this study under saturated steam for short treatment times were close to those obtained by Kauman and Engerhardt; and those obtained for longer treating times were similar to Strickler's results. In this study, the moisture content did not reach equilibrium under saturated conditions and was expected to increase further with treatment time. Therefore, the differences between the reported values for high vapor pressure regions might be due to the difference in treatment time; methods used to obtain the data and the species and dimensions of specimens might be other reasons. For example, Strickler[12] used grand fir, whereas Engelhardt[13] obtained his data with beech. Thus, because the chemical composition and fine structure of wood differ among species, the weight loss by heat treatment and the resulting changes in sorption capacity are diverse.

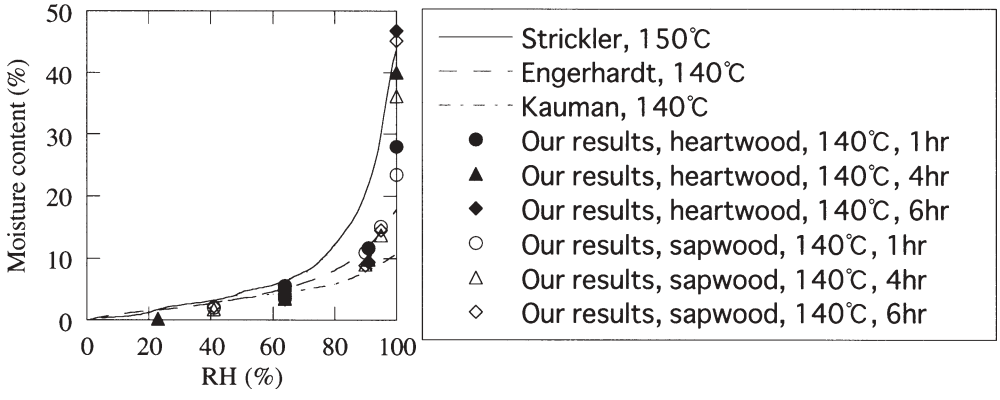

Fig. 7. Comparison of moisture content among reported values. *RH*, relative humidity

Compared to experimentally obtained values, extrapolation of low-temperature moisture content to higher temperatures gives a lower moisture content, around 100% relative humidity (RH). One common technique for the extrapolation involves plotting lines of equilibrium moisture content on a coordinate system of the logarithm of water vapor pressure versus the reciprocal of absolute temperature and extending them to higher temperatures.[21] In many cases equations used for extrapolations have not considered the loss of wood substance by heat and the moisture uptake of wood by condensation. If condensation occurs in or on wood, the moisture content of around 100% RH would become higher and closer to the values obtained in this study.

Conclusions

Wood moisture content in saturated and superheated steam atmospheres was investigated by in situ weighing of specimens and measuring the changes in wood substance. Values for moisture content increased when the loss of wood substance was taken into consideration. In superheated steam the moisture content increased with relative vapor pressure but remained almost constant regardless of treating time. There was not much loss of wood substance in regions of low relative vapor pressure, and it was thought that equilibrium moisture content values obtained by extrapolation might be used for reference. The moisture content increased while in saturated steam as the treatment time and temperature increased. Condensation in wood promoted by chemical decomposition under the closed system was thought to be the reason. The relatively high moisture content in saturated steam at high temperatures may be one of the reasons high-pressure steam works well for wood softening and related wood processing.

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