

RELATION BETWEEN MOISTURE SORPTION AND HYGROEXPANSION OF SITKA SPRUCE DURING ADSORPTION PROCESSES

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Abstract. Moisture adsorption processes carried out in successive steps at three increasing levels of RH (45, 75, 85%) at 20°C for Sitka spruce (*Picea sitchensis Carr.*) were studied. Moisture content and dimensional changes in radial and tangential directions of the specimens were measured and it was found that moisture changes were slower than dimensional. The modeling on this moisture-dimensional relationship, based on the idea of dividing sorbed water into two components having different effects on dimensional changes, not only shows a good agreement with experimental results, but also presents a new understanding of the mechanism of hygroexpansion of wood.

Keywords: Adsorption, dimensional change, moisture change.

INTRODUCTION

Wood as a hygroscopic material, has characteristics such as mechanical properties and dimensional stability that are affected by moisture content (MC). Because environmental conditions (RH and temperature) are rarely constant, wood is continually subject to moisture sorption processes

and at the same time producing corresponding dimensional changes. As a result, it is important to have a good understanding of the moisture sorption of wood as well as its relation with dimensional change.

Various theories have been developed to describe moisture sorption in wood. Many are based on Fick's diffusion law (Stamm 1959; Droin-Josserand et al 1988a, 1988b; Liu et al 2001).

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However, the relation between moisture sorption and time cannot be easily determined because of the complex solution of the Fickian differential equation. In addition, some studies have shown that the equation does not adequately describe moisture movement in small wood specimens and that other processes operate to limit the rate of moisture change in wood (Christensen and Kelsey 1959; Kelly and Hart 1969; Skaar et al 1970; Nakano 1994a, 1994b; Zhang et al 2007). Although much information is available in the literature on the kinetics of moisture sorption, there have been few tests and theoretical models related to dimensional changes during the sorption process. This has been partly because it is difficult to measure dimensional changes during sorption and the focus on sorption. Nakano (1994a, 1994b) proposed a nonsteady state adsorption equation for wood, in which the process was regarded as an autocatalyzed sorption reaction. The mathematical model made a great breakthrough in that it can characterize either moisture or dimensional changes during adsorption.

The work reported here was conducted to investigate the relation between moisture and dimensional changes during sorption process and to try to model and give a tentative explanation of this relationship.

MATERIALS AND METHODS

Wood specimens were prepared from Sitka spruce (*Picea sitchensis* Carr.) with dimensions

of 4 mm along the grain and 20 mm in tangential and radial directions. The specimens were first oven-dried at 105°C, after which their oven-dry weight and dimensions were measured. They were placed in an environmental chamber maintained at $20 \pm 0.2^\circ\text{C}$ throughout the experiment.

The specimens were subjected to successive moisture sorption by increasing RH inside the chamber following a discontinuous stepwise process (45, 75, $85 \pm 1.0\%$ RH) according to a predetermined program. Each step was 48 h, which was determined by pre-experiments so that quasiequilibrium could be attained. Temperature and RH transmitters were placed near the specimens to monitor the conditions. Weight and radial and tangential dimensional changes were recorded by an electronic balance and three CCD laser displacement sensors, as shown in Fig 1. The precision of measurement was ± 0.1 mg and ± 1.0 μm .

In addition, a group of three end-matched specimens was used during the test: one for dimension measurement and the other two for weight. Successive adsorption was repeated three times with oven-dry specimens. The dimensional measurement specimens were rotated so that each of the three specimens was measured for dimension once and weight twice. In this way, the effect of variability among specimens could be reduced considerably. Average values of the three measurements were taken as the final results for analysis.

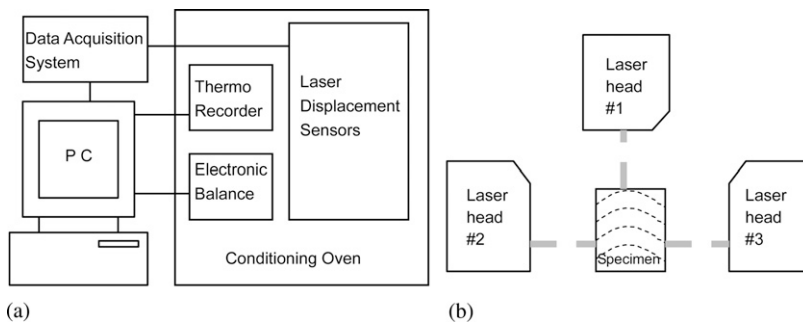


Figure 1. Diagram showing the instrumentation for (a) the entire assembly (b) detecting the dimensional changes in the specimen, in which laser head 1 is for the radial measurement and laser heads 2 and 3 are for the tangential.

RESULTS AND DISCUSSION

General Adsorption Behavior

A general behavior of moisture uptake and hydroexpansion of Sitka spruce during successive adsorption is shown in Fig 2 in which the MC and swelling are calculated based on oven-dry conditions. Both moisture and dimensional changes follow the same trend, that is, the sorption and swelling rate of the specimens are high at the initial stage during adsorption and decrease gradually until equilibrium is reached. In addition, tangential swelling is much greater than radial, especially in the high RH range.

Figure 3 gives detailed information on a comparison between MC and radial swelling for adsorption from oven-dry to 45% RH. The figure indicates that dimensional change reaches an equilibrium state first followed by MC, meaning that moisture changes are slower than dimensional. This agrees with Hunt's (1990) research in which longitudinal dimensional changes of Scots pine were found to act quickly than mois-

ture changes during adsorption and desorption processes. The phenomenon is particularly interesting because moisture change is supposed to be faster than, or at least simultaneous with, dimensional change, because it is believed that swelling and shrinkage are caused by moisture moving in and out of wood (Yin 1996; Bowyer et al 2003). Therefore, this unusual behavior suggests the need for further study on the mechanism of hydroexpansion of wood. Because the relation between sorption and swelling rate is not as obvious for the other two RH ranges, Nakano's adsorption theory was applied to investigate this.

Theoretical Analysis by Nakano's Adsorption Theory

Ma et al (2009) made a modification to the adsorption equation proposed by Nakano (1994a, 1994b) so that it could be applied to adsorption from a specific initial MC. The modified equation can be written as

$$m = (m_e - m_0) / [1 + \exp(-r(\log t - a))] + m_0 \quad (1)$$

or in the case of dimensional changes,

$$l = (l_e - l_0) / [1 + \exp(-r(\log t - a))] + l_0 \quad (2)$$

where m and l are MC (%) and swelling (%), respectively, at time t (s). The subscripts o and e refer to initial and equilibrium states, respec-

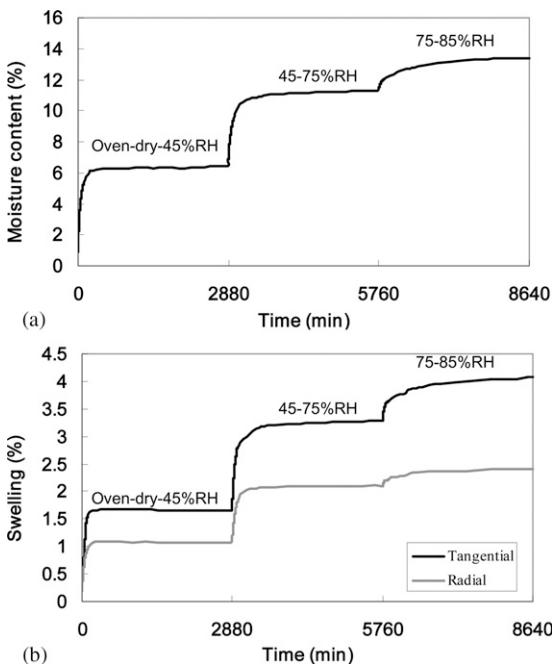


Figure 2. Plots of moisture content (MC) (a) and swelling (b) against time during adsorption processes of Sitka spruce.

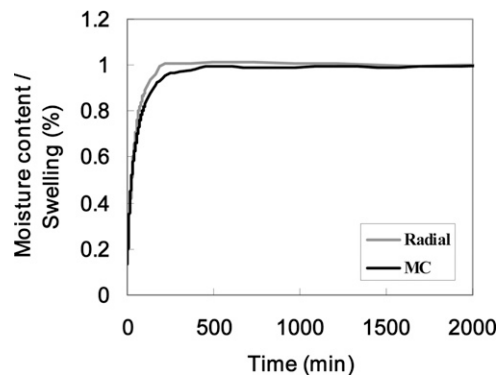


Figure 3. Normalized curves of moisture content (MC) and radial swelling against time for the adsorption of Sitka spruce at 45% RH.

tively, and a and r are constants. Figure 4 shows the MC and moisture sorption rate curves for the adsorption of Sitka spruce at 45% RH. The value of a indicates the time taken for wood to reach a maximum sorption rate and, accordingly, $2a$ is assumed to be the time needed to approach the equilibrium state.

Figure 5 shows a comparison of theoretical curves with experimental results for MC and radial and tangential swelling at various RH conditions. The plots suggest that theoretical curves agree satisfactorily with the corresponding experimental results. The values of a for moisture sorption and radial and tangential swelling are listed in Table 1 as well as the average a value of radial and tangential swelling for each RH condition. It is clear that a increases with an increase in RH, which means that the higher the RH, the longer time needed for wood to reach equilibrium, as shown in Fig 5. In addition, a is greater for moisture sorption than for swelling at a given RH. This suggests that moisture changes are slower than dimensional changes. Furthermore, the data in Table 1 also show that radial a value is always several percent higher than tangential value, illustrating that hygroexpansion is slower in the radial than the tangential direction, which is in accordance with Chomcham and Skaar (1983).

Modeling the Relation between Moisture and Dimensional Changes

Abundant studies have been presented to show that chemical treatment can reduce hygroexpansion

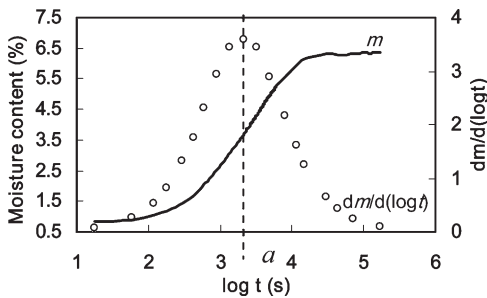


Figure 4. Plots of moisture content (MC) (m) and sorption rate ($dm/d[\log t]$) against $\log t$ for the adsorption of Sitka spruce at 45% RH.

sion and improve dimensional stability of wood (Skaar 1988). In the Hailwood-Horrobin sorption theory (Hailwood and Horrobin 1946), water is presumed to exist in two forms. These

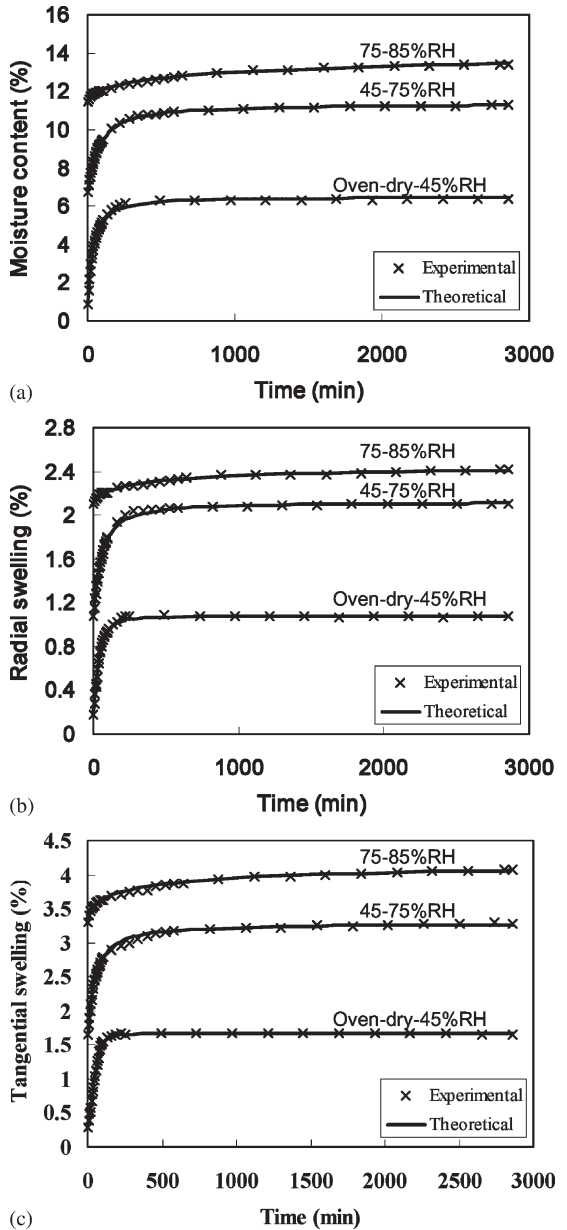


Figure 5. Comparison of theoretical curves with experimental results of moisture content (MC) (a), radial swelling (b) and tangential swelling, and (c) for the adsorption of Sitka spruce.

Table 1. Values of constant a for moisture sorption and radial and tangential swelling.

RH range (%)	Moisture sorption	Radial swelling	Tangential swelling	Average of radial and tangential swelling
Oven-dry-45	3.3953	3.3269	3.2969	3.3119
45-75	3.6111	3.5471	3.5171	3.5321
75-85	4.7016	4.2782	4.1806	4.2294

Table 2. Calculated moisture contents of hydrated and dissolved water with experimental results.

RH (%)	Moisture content (%)		
	Experimental	Hydrated water	Dissolved water
45	6.45	3.27	3.18
75	11.32	4.39	6.93
85	13.42	4.67	8.74

are “hydrated water,” which forms a hydrate with the wood substance, and “dissolved water” that forms a solid solution in the cell wall, bonding only with other water molecules. Yasuda et al (1994) applied the Hailwood-Horrobin sorption theory to their adsorption data of chemically modified wood and found that the amount of dissolved water decreased considerably, whereas hydrated water suffered only from a slight or almost no reduction in MC by the chemical treatment. This indicates that dimensional changes of wood are almost caused by a change in dissolved water.

Therefore, assume hydrated water has little or no relation to dimensional changes and dissolved water is strongly associated with dimensional changes. The Hailwood-Horrobin sorption equation (Hailwood and Horrobin 1946) was then used to calculate the two water components and the results are given in Table 2. To quantify hydrated water and dissolved water during adsorption, Eq 1 was applied separately to these components, and the sum of the two parts was taken as the theoretical total MC that was compared with experimental data.

Moreover, according to the characteristics of hydrated and dissolved water described previously, it is convenient to consider that

1. Moisture contents of hydrated and dissolved water in Table 2 are supposed to be their cor-

responding m_e at the current RH and m_0 for the subsequent RH condition, respectively, and

2. The average a value of radial and tangential swelling in Table 1 is taken as the a value for dissolved water and that of moisture sorption is adopted as the one for hydrated water at each RH.

Therefore, during adsorption, dissolved water develops rapidly, causing dimensional changes of wood to take place quite quickly and reach equilibrium first followed by much slower changes in MC because hydrated water increases slowly with little or no further dimensional changes, as shown in Fig 3.

The calculated MC of hydrated and dissolved water and their total amount during adsorption in comparison with experimental data are shown in Fig 6. It is evident that the theoretical total MC is in good accordance with experimental results for each RH condition. However, the initial MC of hydrated water for adsorption at 45% RH (Fig 6a) is about 1%, which is not an expected value because the specimens were oven-dried. This is perhaps because wood usually has a MC of about 0.5% under oven-dry conditions (Stamm 1964). In addition, the RH error caused by opening the conditioning chamber when inserting specimens at the beginning of the experiment could also be responsible for slightly higher initial MC of hydrated water in the modeling.

CONCLUSIONS

Dimensional changes of wood are suggested to take place more quickly than moisture changes during adsorption in this study. The modeling of this relationship, based on the idea of dividing adsorbed water into two components having different effects on dimensional changes as well as being adsorbed in different modes depending on the RH, not only shows good agreement with experimental results, but also presents a new and interesting viewpoint for the interpretation of this unexpected behavior. It is hoped that the idea could enable one to gain a fuller insight into the moisture sorption process and contribute to a

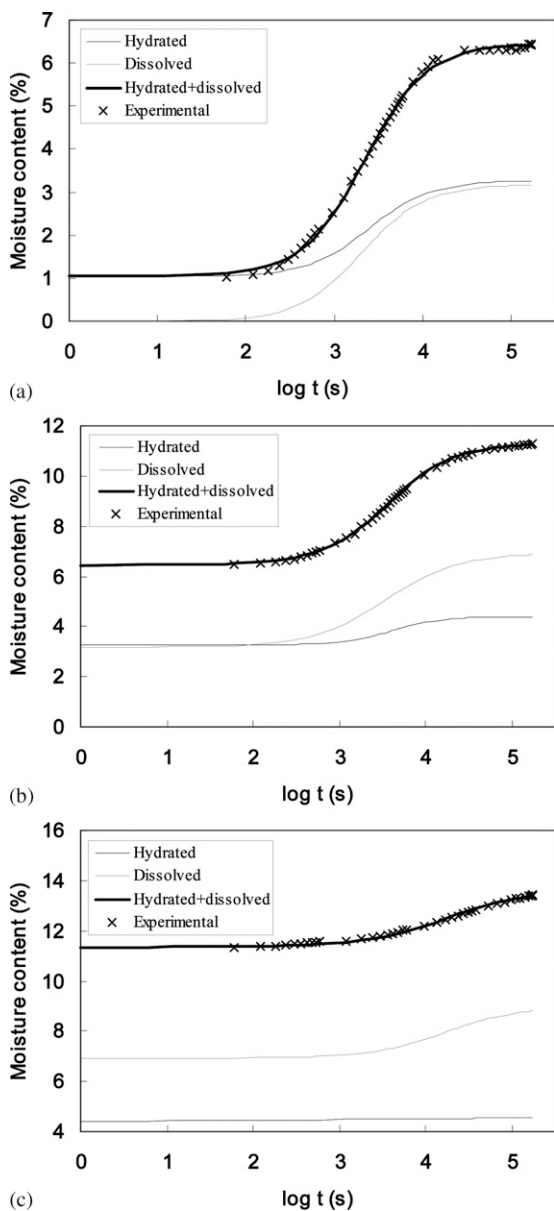


Figure 6. Theoretical moisture content (MC) for hydrated water and dissolved water and their total amounts in comparison with experimental data during adsorption at (a) 45, (b) 75, and (c) 85% RH.

deeper understanding of the mechanism of hygro-expansion of wood. In future work, moisture desorption processes and longitudinal dimensional changes will be investigated.

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