Evaluation of Moisture Transfer in Wood using NIR Spectroscopy during Drying

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The generation of drying stress in wood is initiated by moisture gradients that develop on the surface of wood during air drying. In order to control drying stress, it is important to analyze the movement of moisture on the surface of the wood accurately. Near-infrared spectroscopy can be used to estimate the physical and chemical properties of materials quickly and nondestructively.

In this study, it was intended to measure the moisture contents on the surface of wood for analyzing the moisture movement mechanism using near-infrared spectroscopy coupled with multivariate analytic statistical techniques. It was expected that accurate measurement of the surface moisture content and average moisture content could be used to determine the surface moisture emission coefficient and the diffusion coefficient of wood in unsteady state. It was also expected that a surface moisture content quantification method and an internal moisture content estimation technique would be able to control the drying process and promote the efficient use of wood.

Additionally, the strains that developed on the cross section and circumference surface of wood were measured using a strain gauge while the wood was drying. The drying stresses generated on the surface and in the wood during drying were analyzed by experimental methods. The residual drying stress was evaluated by destructive methods such as a slice test.

Key word: NIR spectroscopy, surface moisture content, finite difference method, drying stress, strain
Introduction

The near-infrared (NIR) rays in the range of 750 ∼ 2,500nm have lower absorptivity, larger reflectivity, and deeper infiltration compared to medium-infrared rays. For this reason, they have the advantage of being able to analyze physical-chemical properties on or around surfaces rapidly and nondestructively without physical pretreatments for convenience of the test. In this study, it was intended to develop a method of measuring the moisture content on the surface of wood using NIR rays.

With the assumption that the moisture content profile in wood in unsteady state can be controlled by determining the surface moisture emission coefficient and the diffusion coefficient, it is intended to determine the surface emission coefficient by measuring the surface moisture content through an application of NIR spectroscopy and the diffusion coefficient through the measurement of the change of the average moisture content of wood. It is expected that the mass transport mechanism in wood in unsteady state as realized in the applied process could be analyzed with a numerical analysis with the coefficients.

Additionally, the temperature change of the material in unsteady state to be realized in the applied process was estimated using the convective heat transfer coefficient as determined in external air condition and the thermal diffusivity was determined with thermal conductivity, density and specific heat of wood.

Finally, the drying strain generated on the surface of the wood was estimated in the drying, and the residual stress in the wood after drying was evaluated by a slice test.

Materials Methods

Materials

Small specimens of yellow poplar (*Liriodendron tulipifera* L.) with a dimension of 50(width, tangential) x 50(length, longitudinal) x 5(thickness, radial) mm were prepared to evaluate the surface moisture contents. These specimens were humidified in various temperatures and humidity levels(Table 1).
Center-bored roundwood of yellow poplar was manufactured with an external diameter of 180mm and with center-boring diameter of 100mm for kiln drying test. The tree used as a sample in the study was aged 35 years with a diameter of 40cm. The initial moisture content of the wood taken from the tree was 80%MC.

**Methods**

To measure the surface moisture contents of the specimens, the near-infrared spectrum was acquired using a NIR spectroscopy (NIRQUEST256-2.5, Ocean Optics) (Figure 1). The NIR spectroscopy used a 35W tungsten-halogen lamp as a light source. The light probe consisted of 6 optical fibers that send light from the light source to a target material and 1 optical fiber that send light from the target material to a detector.

After acquiring the reflection spectrum of specimens humidified at each relative humidity condition, the reflection spectrum was converted to the absorbance spectrum. A surface moisture determination model was established by Multiple Regression Analysis and Principal Component Analysis with the absorbance spectrum varied depending on the surface moisture contents.
Figure 1. Measurement of the surface moisture content of wood using NIR spectroscopy in a temperature and humidity chamber

The surface emission coefficient $S$ is determined by the following formula with the wood’s surface moisture content measured by a near-infrared ray spectrum analysis in unsteady state.

$$\frac{dw}{dt} = S \cdot A \left( \frac{SMC}{100} \cdot G_{SMC} - \frac{EMC}{100} \cdot G_{EMC} \right)$$

$S$: Surface emission coefficient (m/sec)
$w$: Evaporated water weight (g)
$t$: Time (sec)
$SMC$: Surface moisture content (%)
$EMC$: Equilibrium moisture content (%)
$A$: Surface area (m$^2$)
$G_{SMC}$, $G_{EMC}$: Oven dried wood weight/volume of wood at SMC and EMC

In addition, the diffusion coefficient $D$ was determined by the following formula with the fractional average moisture content of wood in unsteady.

$$D = -\frac{4L^2}{t\pi^2} \cdot \ln\left(\frac{\pi^2}{8} \cdot \bar{E}\right)$$

$D$: Diffusion coefficient (m$^2$/sec)
$L$: Half length of specimen (m)
$t$: Time (sec)
$\bar{E}$: Fractional average moisture concentration $= \frac{AMC - EMC}{IMC - EMC}$

$AMC$: Average moisture content (%)
$IMC$: Initial moisture content (%)
Using the Finite Difference Method (FDM) with the surface emission coefficient and diffusion coefficient, the surface and internal moisture content distributions were calculated under a drying condition in 1,000mm long center-bored roundwood with outer diameter of 180mm and inner diameter of 100mm.

\[
C_{m,n}^{p+1} = \frac{t}{(\Delta x)^2} \left[ D_x \left( C_{m+1,n}^{p} + C_{m-1,n}^{p} - 2C_{m,n}^{p} \right) + D_y \left( C_{m,n+1}^{p} + C_{m,n-1}^{p} - 2C_{m,n}^{p} \right) \right] + C_{m,n}^{p}
\]

Convection boundary node
\[
C_{m,n}^{p+1} = \frac{t}{(\Delta x)^2} \left[ D_x \left( C_{m-1,n}^{p} - C_{m,n}^{p} \right) + \frac{D_y}{2} \left( C_{m,n-1}^{p} + C_{m,n+1}^{p} - 2C_{m,n}^{p} \right) + S_{x} \left( C_{x} - C_{m,n}^{p} \right) \right] + C_{m,n}^{p}
\]

Exterior corner node
\[
C_{m,n}^{p+1} = \frac{t}{(\Delta x)^2} \left[ \frac{D_x}{2} \left( C_{m+1,n}^{p} - C_{m,n}^{p} \right) + \frac{D_y}{2} \left( C_{m,n+1}^{p} - C_{m,n}^{p} \right) + S_{x} \left( \frac{\Delta x}{2} \right) (C_{x} - C_{m,n}^{p}) + S_{y} \left( \frac{\Delta x}{2} \right) (C_{y} - C_{m,n}^{p}) \right] + C_{m,n}^{p}
\]

S : Surface emission coefficient (m/sec)
D : Diffusion coefficient (m²/sec)
C : Moisture concentration (g/m³)
\(\Delta x = \Delta y\) : distance (m)

The drying of center-bored roundwood was carried out by follow drying schedule (Table 2). The strains on the surface of the center-bored roundwood were measured using a strain gauge (Kyowa, KFG-5-120-C1-11L1M2R) and a datalogger (TML, TDS-303).
Table 2. Dying schedule for center-bored round wood

<table>
<thead>
<tr>
<th>Time (hr.)</th>
<th>Dry bulb (°C)</th>
<th>Relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-12</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>12-24</td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>24-36</td>
<td>90</td>
<td>50</td>
</tr>
<tr>
<td>36-48</td>
<td>90</td>
<td>40</td>
</tr>
<tr>
<td>48-90</td>
<td>90</td>
<td>30</td>
</tr>
</tbody>
</table>

To measure the internal temperature at a depth of 2.5cm from the side surface, a thermocouple (K type) and a datalogger (Campbell co., CR1000) were inserted. Analysis of the tangential and radial strain on the end cross sectional surface and the side surface of center-bored round wood was carried out. Strain gauges were attached to the cross-section and side surface. In addition, the internal restrained stress was evaluated by slice test after the drying.

Figure 3. Measurement of the temperature and strain of center-bored roundwood

Results

Analysis of the near-infrared spectrum
Figures 4-A and 4-B respectively show the reflection spectrum and the absorbance spectrum of the surface of the humidified specimen. Using the reflection spectrum of each moisture content, the absorbance spectrum was calculated by the formula of ‘absorbance = \log(1/\text{reflection})’. It was found that the absorbance spectrum varied with the MC levels of the specimens.

Because the spectrum peak measured by NIR spectroscopy is affected by the chemical components of the specimens and because it contains signal noise, a moisture prediction model was established after carrying out several numerical pretreatments like Smoothing, Baseline, Derivative, Normalization and Standard Normal Variate treatments. A regression model to predict the surface moisture content could be expressed by the following equation, and the regression coefficients are shown in Figure 5-A. Figure 5-B shows that the regression model predicts the actual surface moisture content very well while ignoring the temperature effect.

\[
Y = b_0 + b_1 x_1 + \cdots + b_k x_k
\]

\(Y\) : surface MC(\%)
\(x_i\) : NIR absorbance at each wavelength
\(b_i\) : regression coefficient at each wavelength

Using surface moisture content data measured by the NIR method under different surrounding temperature conditions, the surface emission coefficients were determined (Figure 6-...
A). using the average MC change as measured by oven dried method at those conditions, the diffusion coefficients were determined (Figure 6-B).

![Figure 6. Surface emission coefficient(A) and diffusion coefficient(B) of specimens](image)

Figure 7 shows the result of the calculated MC of the center-bored roundwood from a numerical analysis (FDM) with the surface emission coefficient and the diffusion coefficient. The surface MC and internal MC of the wood during drying could be predicted at any time.

![Figure 7. Moisture contents profile in center-bored roundwood](image)

**Drying process of center-bored roundwood**

The internal temperature of the center-bored roundwood during drying had reached the target temperature of 90°C after 4 hours and this temperature was maintained (Figure 8-A). The moisture content of the center-bored roundwood of yellow poplar reached 12%MC after 4 days of drying, 96 hours (figure 8-B).
The shrinkage in the radial direction after drying was approximately 5.48%. After 12 hours of drying, a little of drying check in cross-section was observed. The total strain that occurred during the drying was a result of the combined interaction of shrinkage based on the reduction of the moisture and a change of the elasticity and the viscoelasticity of the wood.

In the cross-section, the radial strains were reduced due to shrinkage, but tangential strains were increased due to the development of micro drying check (Figure 9-A). No strains was found in the longitudinal and tangential direction in side surface.

Due to the differing moisture gradients and shrinkage in each section of the wood during drying, the residual stress in the wood during drying appears to vary. On the surface and in the core part, a small amount of tensile stress was discovered.
Conclusion

In this study, it was intended to measure the moisture contents on the surface of wood to analyze the moisture movement mechanism using near-infrared spectroscopy coupled with multivariate analytic statistical techniques.

It was expected that accurate measurement of the surface moisture content could be used to determine the surface moisture emission coefficient and the diffusion coefficient of wood in unsteady state. It was also expected that the surface moisture content quantification method and the internal moisture content estimation technique could be used to control drying process and promote the efficient use of wood.

Additionally strains developed on the cross section and the circumference surface of the wood were measured using a strain gauge during drying. And drying stresses generated on the surface and in the wood during drying were analyzed by experimental methods. Residual drying stress was evaluated by a destructive methods such as slice test.

References

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