A new method of determining moisture gradient in wood

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Abstract

Moisture gradient in wood and wood composites is one of most important factors that affects both physical stability and mechanical performance. This paper describes a method for measuring moisture gradient in lumber and engineering wood composites as it varies across material thickness. This innovative method employs a collimated radiation beam (x rays or γ rays) emitted from a radiation source that discretely scans the material in steps or continuously through its thickness direction. A radiation detector on the other side detects intensities of the transmitted beam, which directly relates to the material density profile through scanning direction. Moisture gradient can be calculated by contrasting it to the ovendried density profile. A series of solid wood samples were tested to verify the accuracy of this technique. The estimated moisture content (MC) gradients measured using the radiation method were compared with the actually measured MC gradients using the ovendry method of microtomed sections. The high correlation between the two MC gradient methods proved that the radiation method could provide an accurate and prompt estimation of internal wood MC gradient.

Moisture gradients in hygroscopic composite materials such as wood are known to affect internal stresses that cause dimensional changes and eventual development of defects. Severe deformation and other defects of finished products reduce product quality and have the potential to damage a manufacturer's reputation and significantly increase the cost of manufacturing. One of the oldest methods for measuring moisture gradient in wood was the bandsaw slicing technique (McMillen 1955). This technique is not entirely accurate because of kerf and moisture losses caused by heat generated during high-speed cutting. Methods of slicing thin layers were improved later by using a drill bit (Feng and Suchsland 1993) and microtone knife (Wand and Youngs 1996). Because the samples were destroyed after measuring moisture gradient, these methods failed to provide a continuous monitoring of moisture movements inside samples. This made it difficult to develop accurate models of moisture gradient and movement during wood drying.

The search for a nondestructive method of measuring moisture in wood started in early 1900. The electrical resistance of wood was found to be a good indicator of moisture content (MC) (Myer and Rees 1926) and was widely used after an extensive study on the electronic properties of wood (James 1963). Instead of using a single parameter (electrical resistance), many advanced devices employed radio frequency signals to measure MC in wood (Dennis and Beall 1977, Steele and Cooper 2006). These methods were based primarily on principles of electrical resistance, capacitance, and phase. Because the relationship between MC in wood and its electrical properties were not fully understood, the radio frequency technique was dependent on experimental data to create an empirical relationship for each species.

Radiation techniques were used to determine MC and density of wood and other materials (Loos 1961, 1965; Gardner et al. 1972; Spolek and Plumb 1981). The principle of these radiation techniques is that penetration of the radiation ray (x ray, beta ray, and gamma ray) into materials is dependent on gross density of the material and how deep radiation penetrated into the material. Estimated density is the average value of volume where radiation penetrates. For nonuniform materials, usually the radiation shapes (spot, plane, or plume) might have some effects on estimated density.

A narrow beam of monoenergetic photons with an incident intensity I_0, penetrating a composite material (i.e., wood) with transmitted distance t and density, emerges with intensity I given by the exponential attenuation law:

$$I = I_0 e^{-\left(\sum_i \mu_i \rho_i\right) t} \quad [1]$$

where μ_i is mass attenuation coefficient of ith component with density of ρ_i in the composite. The mass attenuation coefficient is a basic quantity used in calculations of penetration

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Forest Prod. J. 58(7/8):41–45.

and energy deposition by photons. Given energy of incident radiation depends on material compositions and can be obtained by simple addition, such as combining values for the elements according to their proportions by weight.

By comparing incident intensity I_o and transmitted intensity I, the exponential attenuation law (Eq. [**1**]) will determine the density of a given specimen with a known mass attenuation coefficient and the penetration thickness. The relationship between mass attenuation coefficient and moisture is used to determine MC. Because radiation covers a large portion of the specimen, the method is used to estimate average MC throughout a given volume of wood and is related to size of the radiation plume. When shrinkage initiates as the wood dries to below the fiber-saturation point, MC in wood is no longer linear with density. Therefore, to assure accuracy, all methods require that separate radiation models be used above and below the fiber saturation point.

Hattori and Kanagawa (1985) estimated moisture in wood with a medical x-ray computer tomograph (CT) scanner. In this study, the CT scanner transmitted the x ray through wood samples in their longitudinal direction. The CT images of 35 samples with different MCs (from wet to ovendried) but the same dimensions (2 cm by 2 cm by 1 cm) were analyzed. The CT numbers within the 2-cm by 2-cm square of each sample were used to correlate to average MC of the sample. After establishing a regression model to accurately estimate average MC of small samples, Kanagawa and Hattori (1985) used the same CT scanner to investigate moisture distributions of two 10.5-cm square timber samples during conventional kiln-drying. The CT images were taken through the samples' longitudinal direction on the 10.5-cm square radial–tangential surface. The images were then meshed into 20 by 20 grids of small squares (a series of about 0.5-cm grid squares). Instead of using the basic radiation attenuation law, CT numbers in each small square were counted and used to estimate moisture distributions among the small squares based on the previously discussed average MC-regression model (Hattori and Kanagawa 1985) developed for the entire piece. Moisture distributions estimated using CT images were actually the average moisture in the 400 small grid areas. Moreover, any such regression model will be somewhat dependent on species and the CT scanner.

Xu et al. (1996) investigated a procedure to determine water-absorption distribution in particleboard, medium density fiberboard (MDF), and oriented strandboard (OSB). The procedure was based on direct measurement of the vertical density distribution from a gamma-ray densitometer before and after water soak and vertical-density distribution after the water-soaked specimens had been reconditioned to their presoak weights. The researchers then used these data sets to separate "wood mass" and "water" from different vertical density distributions. Thus, Xu et al. estimated water absorption inside the sample. To separate water from wood mass, the method assumed that wood within a divided volume before soaking is the same location and mass as wood after soaking. However, after water soaking, each layer inside the sample expanded evenly. It is possible to divide the sample into layers so that each pair of corresponding layers before and after water soaking have the same wood weights, but it is impossible to precisely locate those layers after soaking so that they are identical to those before soaking.

Moisture gradient in composite material (wood) is one of important physical parameters that needs to be accurately determined if we are to better understand internal stresses and dimensional stability. The primary objective of our study was to investigate radiation techniques that could be used to determine moisture-content gradient in wood.

Methodology

Wood-based composites usually consist of cellulose, hemicellulose, lignin, extractive, and other chemical additives (e.g., resin and wax). Lindgren (1991) and Macedo et al. (2002) investigated the effect of wood chemical composition on mass attenuation coefficients. After studying the ratios 50/25/25, 25/25/50, and 10/10/80 for cellulose/hemicellulose/lignin, Lindgren (1991) found that the average value of the mass attenuation coefficient was 0.0876 cm^{-1} with a 0.4 percent coefficient of variation (COV). These researchers concluded that no significant changes were found in the mass attenuation coefficient because of composition changes. Laufenberg (1986) found that a small amount of resin and wax in composites had very limited influence on the mass attenuation coefficient. However, the presence of water in samples was found to affect the coefficient (Lindgren 1991, Macedo et al. 2002).

Usually, mass attenuation coefficient is dependent upon the energy of incident radiation. By selecting a proper incident radiation energy level, the mass attenuation coefficient of water could be about the same as that of wood. Equation [**1**] for wood with certain MC m will then be:

$$I = I_0 e^{-\mu \rho t} \quad [2]$$

where μ is mass attenuation coefficient. After calibrating a given material for its mass attenuation coefficient, overall density ρ of the material could be calculated using the radiation method:

$$\rho = \frac{1}{\mu t} \ln\left(\frac{I_0}{I}\right) \quad [3]$$

According to the *Wood Handbook* (USDA Forest Serv. 1999), wood density is defined as:

$$\rho = \frac{W_{wood} + W_{water}}{V_m} \quad [4]$$

where W_{wood} = weight of ovendried wood; W_{water} = weight of water; and V_m = volume at the MC m. The MC of wood on a dry basis is defined as:

$$m = \frac{W_{water}}{W_{wood}} \times 100\% \quad [5]$$

Wood shrinkage normally begins at about the fiber saturation point (usually 30%) and is continuous in a fairly linear manner until the wood is completely dry. Shrinkage of any segment of wood from the green condition (above the saturation point) to any MC is reported and described (USDA Forest Serv. 1999):

$$S_m = S_0\left(\frac{30 - m}{30}\right) \quad [6]$$

and

$$V_m = V_{green}(1 - S_m) \quad [7]$$

where S_m is volumetric shrinkage from the green condition to MC m (<30%), S_0 is total volumetric shrinkage from the green to ovendry condition, and V_{green} is volume measured at the green condition. After taking into account the shrinkage when MC is below 30 percent, material density in Equation [**2**] can be rewritten as:

$$\rho = \frac{W_{wood}\left(1 + \frac{m}{100}\right)}{V_{green}(1 - S_m)} = \rho_{wood}\frac{\left(1 + \frac{m}{100}\right)}{(1 - S_m)} \qquad [8]$$

where ρ_{wood} is wood density based on ovendried weight and green volume. The exponential attenuation law (Eq. [**2**]) can be rewritten as:

$$\ln\left(\frac{I_0}{I}\right)_m = \mu t \rho_{wood}\frac{\left(1 + \frac{m}{100}\right)}{(1 - S_m)} \qquad [9]$$

For a given wood sample with predetermined parameters such as density ρ_{wood}, total shrinkage S_0, and mass attenuation coefficient μ, MC can be calculated using:

$$m = \frac{\mu t \rho_{wood} - (1 - S_0)\ln\left(\frac{I_0}{I}\right)_m}{\frac{S_0}{30}\ln\left(\frac{I_0}{I}\right)_m - \frac{\mu t \rho_{wood}}{100}} \qquad [10]$$

Another practical way to determine MC of the sample is to compare exponential attenuation relationships between the ovendried condition and certain moisture conditions. Specifically, from Eq. [**8**] we have the density of the sample when it is ovendried:

$$\rho_0 = \rho_{wood}\frac{1}{(1 - S_0)} \qquad [11]$$

Similarly, we have the density of the sample when it has MC *m:*

$$\rho_m = \rho_{wood}\frac{\left(1 + \frac{m}{100}\right)}{(1 - S_m)} \qquad [12]$$

If both ovendried density ρ_0 and density with m MC ρ_m in Equations [**11**] and [**12**] are determined from the radiation method using Equation [**3**], MC of the sample can be calculated from:

when $m \geq 30\%$:

$$m = \frac{\rho_m - \rho_0}{\rho_0} \times 100 \qquad [13]$$

when $m < 30\%$

$$m = \frac{\rho_m - \rho_0}{\rho_0} \times 100 \times \frac{1}{\left(1 - \frac{10\rho_m S_0}{3\rho_0(1 - S_0)}\right)} \qquad [14]$$

During wood drying, the sample is usually drying from the green condition to a target MC. The ovendried exponential attenuation cannot be measured until the sample is ovendried.

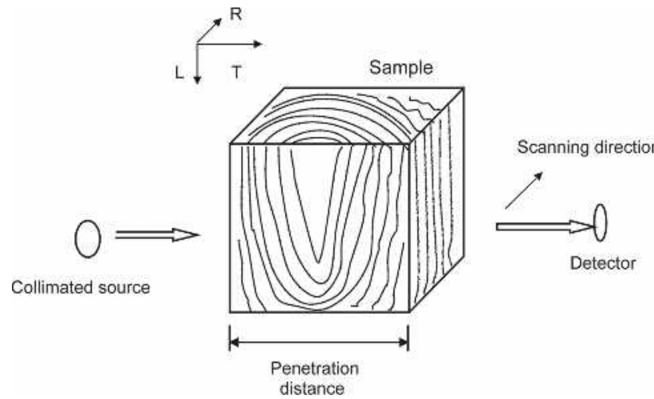

Figure 1. — Typical configuration of radiation measurement of vertical density profiles for a flat-sawn specimen across its thickness (radial direction).

Alternatively, the ovendried density ρ_0 can be estimated earlier by performing the radiation test on the edge of side-matched samples, and the calibrated model could be used to determine the sample MC during drying.

All radiation measurement techniques require a source of radiation and a radiation detector. A typical source detector configuration for measuring density profile across a flat-sawn board thickness is shown in **Figure 1**. Usually, the radiation beam is passed through a slit to provide a collimated x-ray beam that penetrates the sample. Dimension of the sample is typically 50.8 by 50.8 by 20.3 mm, which is in L by T by R directions. The collimated x-ray beam penetrates the sample through either its longitudinal or tangential directions. The collimated radiation beam then incrementally scans the sample at multiple sites through the thickness direction (usually radial). The scanning result will produce a continuous density curve which is called a vertical density profile (VDP). **Figure 2** shows typical ovendried density ρ_0 profile and ρ_m profile for the same sample at MC m. Comparing the two profiles, Equations [**13**] and [**14**] can be used to determine moisture gradient along the thickness direction. We noticed that sample thickness changed when MC of the sample was different, especially when the MC is below the fiber saturation point. Thus, it is necessary to precisely map the two profiles to ensure that ρ_0 and ρ_m match. Equation [**6**] can be used to compensate thickness shrinkage according to the moisture profile.

Test procedures and results

Eight solidwood samples (four oak samples, two pine samples, and two spruce samples) with nominal dimension of 50.8 by 50.8 by 20.3 mm (L by T by R directions) were equilibrated at 22 °C and 65 percent relative humidity (RH) and tested to verify the technique previously discussed. Equilibrated samples were then edge-sealed and ovendried for 24 hours under temperatures of 105 °C. The samples' ovendried density profiles were measured using QMS[1] x-ray density profiler (QMS, Knoxville, Tennessee). Then samples were placed in water with one L by T face submerged and about half of each sample block immersed in water to purposely induce moisture gradients in the radial direction of the

[1] QMS is a trademarked product. Any reference in this paper is not an endorsement but provided for the benefit of readers.

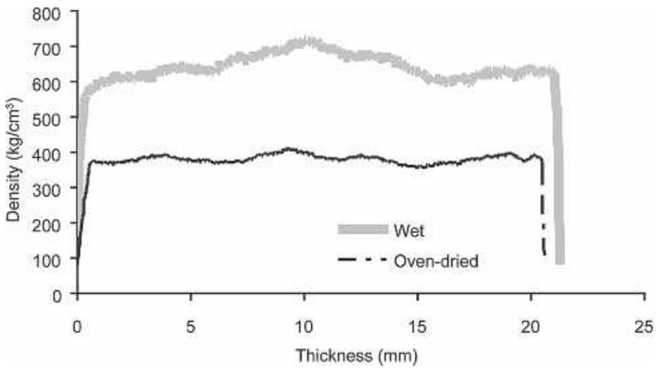

Figure 2. — Vertical density profiles of a sample when it is wet and ovendried.

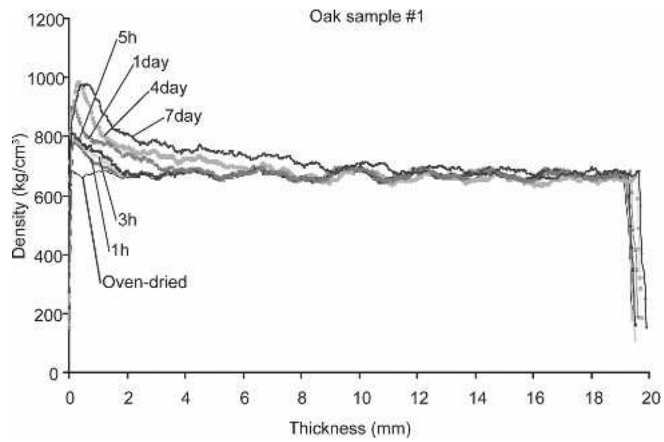

Figure 3. — Density profiles of a typical oak sample when it was soaked in the water from one side for different intervals.

samples. Samples were then taken out at different time intervals for density-profile measurements as shown in **Figure 1**. Each sample had to be dimensionally measured and weighed before it was placed in the QMS x-ray density profiler to test. This is the potential biggest hurdle to applying this technique in wood drying, because the small samples could lose considerable moisture during the transportation from a dry kiln to the density profiler. **Figure 3** shows density profiles at different intervals for a typical oak sample with inducing moisture penetration from one side. After 7 days, all samples were sliced in the radial direction with a microtome knife. Each sliced layer (about 1-mm thick) was carefully marked and ovendried to determine individual MC of each microtomed lamina according to Eq. [**5**]. These data were then plotted across the radial direction to estimate actual moisture gradient. About 12 to 14 layers were sliced from the surface that was immersed in water.

Figure 4 shows the measured moisture gradient and estimated moisture gradients for the same specimen of Oak #1. The measured moisture gradient was determined using the microtome ovendry method after 7-day immersion in water. Estimated moisture gradients were determined using VDP information obtained using the x-ray profiler at various immersing intervals and could be used to estimate moisture gradients over the course of immersions. **Figure 4** shows that estimated gradients seem uneven and overly sensitive. The reason is that sample thickness changes as wood absorbs moisture (below the saturation point) and it is impossible to exactly match ρ_0 and ρ_m when thickness changes. Although Equation [**6**] was used to compensate thickness shrinkage according to the moisture profile, the ρ_m profile could slightly offset the ρ_0 profile. In addition, dimension changes (i.e., warp, twist, and cup) during moisture absorption and density differences between late- and earlywood could also make moisture gradient uneven.

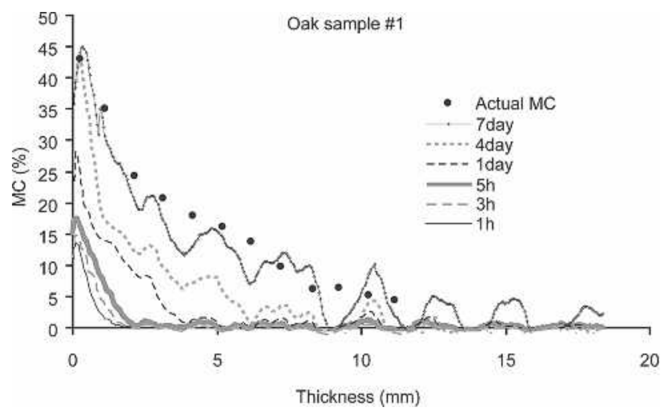

Figure 4. — Estimated moisture content (MC) gradients and actually measured MC gradient after 7-day soak in water.

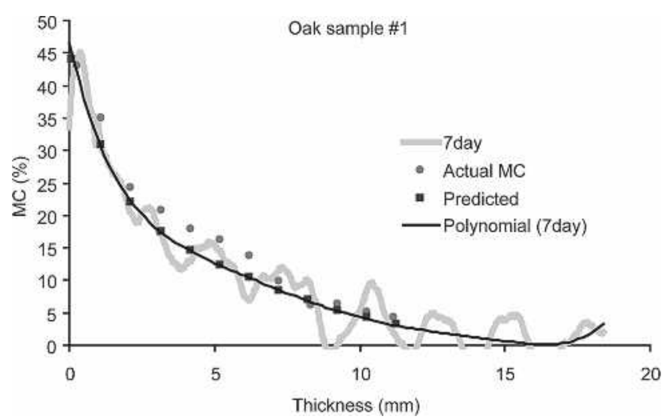

Figure 5. — Comparison between estimated and measured MC gradients.

Comparison between estimated gradient and actual measured gradient after 7-day immersion in water indicated that the two gradients matched well. After the estimated MC gradient was smoothed using a polynomial regression method, estimated MC gradient was thought to more accurately match the measured gradient. **Figure 5** shows the smoothing MC gradient and **Figure 6** presents high correlation between the two MC gradients. The similar procedure was used to analyze data for other samples and species. **Table 1** shows correlation coefficients between the estimated MC gradient and actual measured MC gradient for the eight samples before and after smoothing the MC profile. The high correlation (average R-square after smoothing is 0.97) indicates that the radiation method discussed in this paper provides an accurate and rapid estimation of MC gradient.

The new method could provide a very useful tool for understanding internal moisture movement and moisture-related stress development. The prompt information about internal MC gradient could help to dynamically control wood drying processes. Information about inside moisture distribution

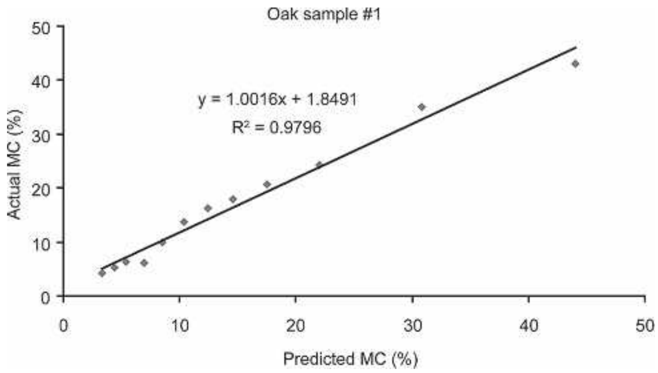

Figure 6. — Linear regression between estimated and measured MC gradients.

Table 1. — Regression coefficients between the estimated and measured MC gradient.

	Linear regression			Linear regression after smoothing		
Wood ID	Slopes	Intercepts	R-square	Slopes	Intercepts	R-square
Oak #1	0.94	3.20	0.93	1.01	1.85	0.98
Oak #2	0.94	5.81	0.81	1.11	2.55	0.97
Oak #3	0.78	12.58	0.32	1.16	1.72	0.95
Oak #4	1.11	3.34	0.79	1.12	−0.16	0.96
Pine #1	1.07	13.79	0.70	1.11	−0.46	0.98
Pine #2	0.80	13.96	0.98	1.01	4.68	0.99
Spruce #1	0.77	4.50	0.97	0.80	3.57	0.98
Spruce #2	1.19	0.25	0.98	1.10	0.95	0.98

could also assist in understanding warping performance of wood composites and allow engineers to find solutions to minimize product-dimensional instability.

Summary and conclusion

We have described a new method using a radiation method to determine moisture gradient of a rectangular- or square-shaped material. This inventive method employed a collimated radiation beam (i.e., x rays or γ rays) from a radiation source. The radiation beam scans material through its thickness direction continuously or discretely. A detector with the same scanning speed is placed on the other side of the material and detects the transmitted radiation beam accordingly. Because the linear attenuation coefficient between the transmitted and incident radiation beam is related to density, the signal from the detector will provide the material density profile through scanning direction. After obtaining the density profile, moisture gradient can be calculated on the basis of dimensional compensation and the previously determined or estimated dried-density profile. Calculated moisture gradient is highly correlated through a polynomial regression technique to actual measured moisture gradient. The new method can be used to monitor internal moisture movement in lumber to provide prompt information about internal stresses that could result in warping and defect development. The method could be useful to dynamically control the kiln-drying process by accounting for internal moisture gradient. This technique could reduce drying time and defects and thereby lower drying energy and improve lumber value.

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