1.0 Introduction and Background

Reduction in drying time and energy consumption offers the wood industries a great potential for economic benefit. But the reduction in drying time often results in an increase in drying related defects such as checks, splits and warp. Most of these defects are caused by drying stresses which are developed from moisture gradients and restrained shrinkage within the wood. So the key to improving drying quality and reducing time lies in understanding and controlling moisture movement in wood during drying (Rice 1988).

Drying quality of most wood products is mainly dependent on the distribution of moisture, especially for hardwoods. Since most hardwood species are dense and moisture movement is difficult, they are hard to dry and are prone to degrade. Red oak is one of the species frequently used in the US furniture and flooring industries, but the drying degrade is particularly acute in red oak (Rice 1988). So red oak is one of the most commonly chosen species for studying drying quality.

Historically the measurement of moisture gradient in wood during the drying period has been made by the slicing method (McMillen 1955). The mechanism of the slicing method is cutting a small wood block into slices along its moisture movement direction, measuring the moisture content of each slice by the ovendry method, and getting the moisture distribution in the wood block. The theory of this slicing method is reasonable, but the results are not ideally accurate because slices for measuring the moisture gradient are thin and sensitive to the environment. Many external factors affect the moisture content of slices, such as the humidity of environment, the high temperature effect from the cutting tools, and material loss, etc. The best technique for accurately measuring the moisture gradient in wood has not been found so far.

The bandsaw slicing technique for measuring moisture gradient is a popular technique used in the wood drying industry. The Forstner bit layering technique (Feng & Suchsland, 1993) was developed as an improved method to overcome the two disadvantages in the bandsaw slicing technique----kerf loss during the slice cutting and moisture loss during the cutting and between the cutting and weighing procedure. In this study, two new techniques----flaking and razor blade slicing, were proposed and compared with the two existing techniques found in the literature.

Flaking and razor blade slicing techniques were developed to reduce material loss, temperature effect, and moisture loss in the bandsaw slicing and Forstner bit layering techniques. The flaking technique uses the CAE flake equipment to obtain thin slices without any kerf loss or temperature effect. The advantage of this technique is that it allows slices thinner than the slices obtained from the bandsaw slicing or Forstner bit layering technique. This would be useful for measuring the moisture gradient in the surface range, which is the critical part for moisture gradient development early in drying. Since in this critical area, the moisture gradient is usually very steep. The more steep the moisture gradient, the higher the stress and strain generated in the wood. The more detailed the moisture gradient we can get, the more help it would be to the study of drying stress and strain.

The razor blade slicing technique developed in this study is almost the same as the bandsaw slicing technique, but without kerf loss and high temperature effect during the cutting procedure because slices are separated with a razor blade which is not a high speed cutting tool.

Both new techniques were developed to overcome the moisture loss problem ---- usually found as a major problem in measuring moisture gradients, through weighing the samples before and after each slice cutting instead of weighing the individual slices. Only the environmental conditions would affect the moisture gradient measured by these two new techniques. But by carefully designing the test procedure, such as quick weighing the samples, wrapping the samples at any necessary occasion, the environmental effect could be controlled to some extent.

Because of the generation of heat from friction during processing of slices, all the techniques have the potential for lowering the moisture content of each slice, particularly as the slice thickness decreases. The thinner the slices, the more information would be available for the study of drying stress and strain, but unfortunately the thinner the slices, the more sensitive they are to the environment. So tests were also done on the effect of slice thickness to provide the appropriate slice thickness for measuring moisture gradient that is least affected by the environment and processing.

Based on the most reliable technique and thickness of slice obtained from the first two tests, experiments were further done on testing the directional effect on the moisture movement during the wood drying. A lot of research has been done on the difference of diffusion coefficient, water conductivity and shrinkage between the radial and tangential directions (Barefoot 1963, Clouties & Fortin 1993, Li & Plumb 1994, Shupe et al. 1995, Wu & Milota 1995 among others). Measurements of moisture gradients along the radial and tangential directions were made in this study to compare the drying speeds in these two directions.

All the tests in this study were done on red oak, because it is one of the popular hardwood species in US and difficult to dry without defects. The results of this study will have considerable economic implications for the wood product industries.

1.1 Objectives

Traditionally the method for measuring moisture gradients in wood has been to cut a piece of wood into slices, measure the moisture content of each slice using the oven-dry method according to ASTM D-2016-83 (1986), and get the moisture distribution through the thickness of the specimen. Due to the sensitivity of thin slices to environmental conditions of temperature and relative humidity and heat from the cutting procedures, moisture content may deviate from its true value. So in turn, the moisture gradient in wood derived using this method is affected.

Due to the problems with previous methods, the first objective of this study was to compare the four techniques for measuring the moisture gradients in red oak during kiln drying and to find the most reliable technique. Two techniques are found in the literature--bandsaw slicing and Forstner bit layering. Two are developed in this research--flaking and razor blade slicing.

The moisture gradient measured in wood depends on the thickness of slices. So the second objective of this study was to test the thickness effect of slices on measuring moisture gradients in wood using the two newly developed techniques.

Finally, based on the reliable technique and appropriate thickness of slice for measuring the moisture gradient, the differences of moisture gradients in the radial and tangential directions were tested.

1.2 Moisture Content Measuring Method

The American Society for Testing and Materials (ASTM) has established three standard methods for measuring the moisture content of wood. One is instantaneous with moisture meters, and the other two are oven-dry and distillation methods (ASTM D-2016-83 1986). Moisture content(MC) of wood is often determined with moisture meters or by the oven-dry method in the wood industries.

That the electrical properties relate to the moisture content of wood, such as conductivity, dielectric constant and power-loss factor has been extensively studied. There are several types of moisture meters. Resistance MC meters are based on the relationship between the electrical resistance (or conductance) and the moisture content of wood. Capacitance MC meters measure the electrical capacitance of wood. Power-loss MC meters measure the loss factor of wood. Both capacitance meters and power-loss meters are based on the relationship between dielectric properties and moisture content of wood. These are popular moisture meters used in the wood industry.

There are also some other moisture meters based on the radiation absorption-related properties of wood, like the infrared moisture gage used in the paper-making industry and the radiofrequency moisture meter. Infrared radiation is selectively absorbed by the water molecule. Beutler (1965) developed a non-contacting, on-line, two wave-length infrared backscatter moisture gage to measure the moisture content of paper, and found that the accuracy of moisture measurement was at least as good as that obtained by the standard gravimetric technique. A surface-contact-type, portable, radio-frequency moisture meter was developed by Dennis & Beall (1977), which responds to water in wood over a wide range of moisture contents. They performed tests on nine 4/4 hardwoods with this moisture meter and developed calibration curves for each species and drying condition. Busker (1968) developed a non-contacting microwave moisture meter and showed that moisture within a 30-100% range in various materials such as paper, tobacco, and textile could be effectively measured.

The moisture meter is a popular method in the industry for its rapid and nondestructive advantage. But these advantages are compromised by the low degree of accuracy. The oven-dry method has been considered as one of the most accurate methods so far for measuring moisture content in wood, but it is destructive and drying time is required.

The ovendry method has been found inappropriate when used for species with a high volatile extractive content. Helmuth & Barton (1963) performed tests of measuring MC on two species with high volatile content and compared the moisture content values determined by the Karl Fischer method which is based on the titration theory and the oven-dry method. They found that the oven-dry test gave higher values than did the Karl Fischer method. They stated that the Karl Fischer titration method was superior. Also William (1992) did a study on 13 eastern redcedar heartwood samples and showed that oven-drying was not a satisfactory method of determining heartwood moisture content. The distillation method proved to be more accurate.

With the use of radiation methods becoming prominent in measuring quality of materials, wood technologists became interested in utilizing these radiation methods for rapid, accurate, and non-destructive physical measurements of wood properties. Loos (1961) first used the gamma ray transmission technique to determine the relationship between gamma ray attenuation and specific gravity and moisture content. He concluded that if the gamma ray attenuation, the thickness, and the specific gravity of a piece of wood were known, moisture content could be determined in its complete range through the model he made. Later, he (Loos 1965) reviewed the principles of radiation methods and summarized the four commonly used radiation sources----alpha, beta, gamma, and neutron in the wood science research. He concluded that the radiation technique for determination of moisture content in wood was best suited for the measurements above the fiber saturation point. Then he hypothesized that it was possible to measure both moisture content and density of wood simultaneously by using a combination of radiation techniques or radiation combined with other techniques. Olson et al. (1982) used an error analysis to empirically and mathematically evaluate a dual-energy gamma radiation method for wood moisture content measurement. They concluded that both the errors made in the water-wood component technique and elemental oxygen-carbon component method were too large to show that the dual-energy gamma radiation technique was suitable for the moisture content measurement. This was partly because of the small difference in mass attenuation coefficients between wood and water. After this, they tested a third method which employed measurement of the total attenuation and the photo-elastic effect. By manipulation of the equations, moisture content of wood could be estimated. But they stated that the complexity and high cost of this measuring system would limit the use of this method.

The nuclear magnetic resonance technique was introduced in wood science research by Magnusson & Eriksson (1972). The technique was developed based on the theory of interaction between the nuclear magnetic moments of individual atomic nuclei and an external magnetic field. They state: “Since different isotopes have different magnetic moments, resonance will take place at different frequencies. Moreover, the resonance signal of a certain isotope may depend on the molecular surrounding of the nucleus or its state of motion.” So it is possible to introduce this technique into measuring moisture content in wood. They showed the feasibility of this approach through testing small wood samples and pulps. Through tests and comparisons, they concluded that very reliable results might be obtained and the accuracy is at least good as that of the oven-drying method used for calibration, especially for small wood samples with moisture content from 0 to 60%.

Since moisture content affects the absorption of infrared radiation, Moksin (1993) stated that it was possible to use the opto-thermal transient emission radiometry measuring system to obtain information on moisture content. But this hasn’t been tested by experiments.

Speed of propagation of an electromagnetic wave is reduced when it travels through matter. This reduction in speed is in proportion to the dielectric constant of the matter. Based on this theory, James et al.(1985) developed a microwave method for measuring moisture content, density and grain angle of wood. In their study, they found that the attenuation of a particular microwave as it was transmitted through a wood specimen was predominantly reflected by the moisture content in wood. The principles developed by this research showed the microwave method to be feasible for nondestructive testing of moisture content of lumber in production. But the apparatus and techniques were very complex. Moreover, the attenuation, phase change and depolarization of a microwave beam interacted extensively, so the data reduction is complicated. Pavol Danko (1994) performed some tests of measuring wood moisture content with the microwave method on three species----oak, spruce and maple and found the same results as James et al.(1985), that moisture content of wood was the most important factor affecting the microwave attenuation. Then Danko further tested some other factors and found that the anatomical directions (such as tangential and radial) and the sample thickness also showed an influence on the microwave attenuation. King & Basuel (1993) developed a two-parameter (attenuation and phase), single-frequency (10 GHz), non-contacting microwave transmission system to simultaneously measure the partial water and dry wood basis weights, the total basis weight and the moisture content. Through extensive experiments, they showed considerable promise for this two-parameter microwave homodyne system for continuos, on-line determination of wood properties.

Troughten (1987) developed a new method to measure moisture content in unseasoned veneer and lumber using basic heating principles. Through laboratory experiments, he derived an equation to describe the relationship between moisture content and surface temperature rise. The moisture content was measured for unseasoned veneer and lumber over a range of 30 to 200 percent. Good results were achieved in a mill trial using this method, so he concluded that this new moisture measuring method had good potential for sorting unseasoned wood into moisture content ranges for more effective drying. Then Kotok et al. (1989) studied some more parameters during drying to try to find the relationship between them and moisture content of wood. Through multiple regression analysis, they found that the surface temperature and elapsed time in the oven could be used effectively for monitoring the average moisture content of wood during drying, and they also stated that infrared sensing devices could be used as a promising measurement of surface temperature.

1.3 Moisture Gradient Measuring Method

Limited literature can be found on the research of moisture gradient measurement. The most commonly used method for measuring moisture gradient in wood is the bandsaw slicing technique presented by McMillen (1955). But this traditional technique is bound to cause inherent errors in the results of moisture gradient measured in wood because:

- moisture is lost due to the high temperature effect when cutting each slice;
- moisture is lost between cutting and weighing slices due to the sensitivity of thin slices to the environment;
- kerf loss when cutting each slice;

Moisture gradient is not easy to measure by non-destructive method because moisture in wood is associated with many other properties of wood, such as density (or specific gravity) and temperature.

Hattori & Kanagawa (1985) used a medical X-ray CT (computer tomograph) scanner to estimate moisture distribution in wood. They estimated the moisture distribution by comparing the CT images of wet and oven-dried wood, studying the relationship between CT number and the density of oven-dried wood. And they found only 1.1% standard error was obtained on the test pieces with a moisture content range of 2-27%.

Gorvad & Arganbright (1980) did a test on comparing the effect of sawing and slicing on the moisture content of wood sections that are used to assess moisture content gradients in lumber. Through experiments on Douglas-fir and tanoak, they found that moisture content loss in cutting sections increased with decreasing section thickness for both slicing and sawing. Above 2.38mm (3/32 inch) section thickness, the larger diameter saw (metal slitting saw) produced moisture content losses less than or equal to losses in sliced sections made with a modified commercial horizontal wood slicer.

Early in the 1960's Hart (1964) provided the principles of moisture movement in wood and the major factors affecting this movement. He divided moisture movement for the unsteady state into two periods: 1). the moisture gradient advanced from the surface to the center of the specimen but no moisture change occurred at the center; 2). the moisture gradient reached at the center and kept approaching equilibrium. Then he derived an equation for calculating moisture gradient in the second period:

$$\frac{Mx - Mo}{Ma - Mo} = \sin\left((\pi/2)\, (x/a)\right)$$

where Mx ---- moisture content at depth x;

Ma ---- moisture content at the center (depth a);

Mo ---- equilibrium moisture content on the surface of wood.

Wang & Youngs (1996) used a microtome knife to remove 1mm-thick slices from the wafer being dried in the chamber. They found that the moisture gradient was concentrated in the outer 4mm of the wood during that period of drying, then they focused on studying drying stress as a result of moisture gradient in the wood.

Later Chen et al. (1996) described a nondestructive approach ---- a numerical analysis technique to evaluate the moisture-dependent diffusion coefficient using drying curves, which gave an accurate prediction of moisture movement through the entire drying process. He used the three-level finite difference scheme as follows to get the moisture profile in wood during drying.

$$(m_{i+1,j} - m_{i-1,j}) = 2/3*\rho\{D_1*[(m_{i+1,j+1}-m_{i,j+1})+(m_{i,j+1}-m_{i,j})+(m_{i-1,j}-m_{i-1,j})]-D_2*[(m_{i+1,j}-m_{i+1,j-1})+(m_{i,j}-m_{i,j-1})+(m_{i-1,j} - m_{i-1,j-1})]\};$$

where $\rho=\Delta t/(\Delta x)^2$;

m is the fractional moisture based on the oven-dry weight, t is the drying time and x is along the thickness of the sample, and i,j refer to the location of m along the t and x coordinates. Δt and Δx were 0.01 hour and 1/10 of the sample half-thickness;

$$D_1=a_0+a_1*[(m_{i,j-1}+m_{i,j})/2];$$

$$D_2=a_0+a_1*[(m_{i,j}+m_{i,j-1})/2];$$

for the surface moisture content, $Ms=Me+(Mi-Me)\exp(-\beta t)$

where Me----equilibrium moisture content;

Mi----initial moisture content.

After the constants a_0,a_1,β are determined, a theoretical drying curve can be generated. By comparing the theoretical moisture content profile with the practical one deriving from the experiment data with the traditional slicing technique for measuring moisture content profile during drying, the optimum parameter values could be found if they would yield the minimum absolute value of Negative Mean Sum of Squares (NMSS), defined as -$\Sigma(\Delta m)^2/N$. Here Δm and N represent the difference m between the theoretical drying curve and the experimental data, and the number of data points, respectively. They performed this numerical technique to get drying curves under two conditions----drying below the FSP; drying from above the FSP to below the FSP. They found when drying below the FSP, the diffusion coefficient is a function of moisture content, and the assumption that the surface moisture content dropped immediately to equilibrium with surroundings is valid; when drying from above the FSP to below FSP, the diffusion coefficient can be considered a constant, the prediction of the drying curve will be improved if it is assumed that the surface moisture content decays exponentially to equilibrium with the surroundings.

Conners & McLain (1988) did a study on modeling moisture gradient effects on bending properties. They extended the common one-dimensional parabolic model for moisture distribution in drying wood into a two-dimensional model. Although the diffusion coefficients for the radial and tangential directions are usually unequal, they said the discrepancies were not significant.

$$MC= 2.25\times(\cancel{MC} - EMC)\times(1.0-k_1\times X^2)\times(1.0-k_2\times Y^2)+ EMC$$

where

MC=moisture content (%) at coordinate (X,Y);

X=horizontal distance from the centroid;

Y= vertical distance from the centroid;

$\overline{MC}$ =average moisture content (%);

EMC=equlibrium moisture content (%);

k_1=1.0/(w/2);

k_2=1.0/(d/2);

w=width of the cross-section;

d =depth of the cross-section;

Feng & Suchsland (1993) developed an improved technique for measuring moisture gradients in wood by using a Forstner bit drill to get each layer of sample. This method overcame the two disadvantages of the bandsaw slicing technique ---- kerf loss during slice cutting and moisture loss between slicing and weighing. Through the experiment comparison, they stated that the Forstner bit layering technique offered a superior method for the determination.