3.0 Results and Discussions

3.1 Comparing the four techniques for measuring the moisture gradient

The moisture gradients within the red oak blocks were measured with the four techniques on five different drying days as previously described. The four techniques were bandsaw slicing, Forstner bit layering , flaking and razor blade slicing technique. The five testing conditions were green condition, after 2 days, 4 days, 6 days and 8 days kiln drying. The moisture content of each slice, flake or layer of wood removed obtained by the ovendry method was assumed to be the average moisture content of each slice, flake and each layer of wood removed, no matter what the thickness of each was. So when plotting the moisture content vs. the position in the red oak block, each moisture content obtained was plotted at the center position of each slice, flake or each layer of wood removed. The moisture profiles in the block on five testing days are depicted in Figures 3.1-3.4 measured by each of the four techniques.

The moisture content under the green condition was almost uniform as seen in the figures. The moisture contents of the outer part excluding the two surfaces were slightly higher than the moisture contents of the inner part. The lower moisture contents of the two surfaces were due to the moisture loss when trimming the samples and the equilibrating effect with the environment.

After the first two days' kiln drying, a moisture gradient was generated in the red oak block. Moisture loss within the first 2 days drying was much more than those in the following 6 days drying. The moisture contents of the surfaces went to the EMC of the condition in the kiln quickly, and didn't change much during the later drying procedure. The slope of the moisture gradient was decreasing with the drying time, which meant the moisture potential was decreasing. So the moisture loss was decreasing with the drying time. It can be concluded that wood drying is becoming more difficult with the increasing of drying time.

To compare the four techniques for measuring the moisture gradients, the results obtained on each of the five testing days with all the four techniques are shown in Figures 3.5-3.9. Third order polynomial regression lines were made for each moisture gradient profile obtained after 2 days drying. Single factor ANOVA tests for the four techniques were performed with the data obtained under the green condition.

The ANOVA (analysis of variance) test is used to decide if the differences among the sample means are large enough to imply that the corresponding population means are different. Since under green condition the moisture content within the block is almost uniform, it could be assumed to have no moisture gradient in the block. So the moisture contents obtained by the four techniques at all positions along the thickness were averaged to get the sample means of the four group populations for the ANOVA test and t-test statistical analysis. The results are shown in Table 3.1 and Table 3.2. ANOVA analysis showed that the results obtained by the four techniques were significantly different because the F-value was much higher than the critical F-value. The average moisture content of all positions measured by the Forstner bit layering technique were the highest as shown in Table 3.1, and the moisture profile shown in Figure 3.5 was also the highest one among the four profiles. The variance of the data obtained by the Forster bit layering was the highest, too. The average moisture content and moisture profile obtained by the bandsaw slicing technique were the lowest as shown in Table 3.1 and Figure 3.5. The flaking and razor blade slicing results were very close to each other, and between the results of the Forstner bit and bandsaw slicing technique. The variance of the flaking result was a little higher than that of the razor blade slicing technique. From the result of T-test analysis for comparing every two techniques in Table 3.2, only the flaking and razor blade slicing results were not statistically different from each other.

Third order regression lines for each moisture gradient on the four testing days measured by the four techniques are shown in Figures 3.6-3.9. Third order regression was chosen because it showed a little higher R^2 value than the parabolic regression that

Table 3.1. Statistical ANOVA analysis of the four techniques under the green condition.

SUMMARY

Groups	Count	Sum	Average	Variance
Forstner bit layering	13	1144.1	**88.00803**	**15.7955**
Flakering	13	1093.88	**84.14445**	**7.01698**
Razor blade slicing	13	1092.8	**84.06119**	**5.06338**
Bandsaw slicing	13	1013.31	**77.94691**	**5.36539**

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	674.479	3	224.8264	**27.0539**	**2.16762E-10**	**2.79806**
Within Groups	398.895	48	8.310302			
Total	1073.37	51				

Table 3.2. Statistical T-test for comparing every two techniques of measuring moisture gradients under the green condition.

(Bandsaw slicing vs. Forstner bit)	
t Stat	-7.885909
P(T<=t) one-tail	1.037E-07
t Critical one-tail	1.7291313
P(T<=t) two-tail	2.073E-07
t Critical two-tail	2.0930247

(Forstner bit vs. Flaking)	
t Stat	2.916598
P(T<=t) one-tail	0.004124
t Critical one-tail	1.720744
P(T<=t) two-tail	0.008248
t Critical two-tail	2.079614

(Flaking vs. Razor blade slicing)	
t Stat	**0.0863683**
P(T<=t) one-tail	**0.4659606**
t Critical one-tail	**1.71387**
P(T<=t) two-tail	**0.9319211**
t Critical two-tail	**2.0686548**

(Bandsaw slicing vs. Flaking)	
t Stat	-6.3502271
P(T<=t) one-tail	7.247E-07
t Critical one-tail	1.7108823
P(T<=t) two-tail	1.449E-06
t Critical two-tail	2.0638981

(Forstner bit vs. Razor blade)	
t Stat	3.11585
P(T<=t) one-tail	0.002845
t Critical one-tail	1.729131
P(T<=t) two-tail	0.00569
t Critical two-tail	2.093025

(Bandsaw slicing vs. Razor blade)	
t Stat	-6.8265405
P(T<=t) one-tail	2.317E-07
t Critical one-tail	1.7108823
P(T<=t) two-tail	4.635E-07
t Critical two-tail	2.0638981

had been done before the third regression was made. Ray (1988) stated that usually an equation of the fourth order is sufficiently accurate. Some researchers believed that third order is near standard. Fourth order regression was also performed when analyzed the results, but there was not much difference in R^2 values between those of the third order regression, and the fourth order terms in the equations were much smaller. So the third order regression equations for the moisture gradients within the block and correlation coefficients are presented in Table 3.3.

Regression lines of moisture gradients measured by the flaking and razor blade slicing techniques were close to each other and between the lines measured by the Forstner bit layering technique and bandsaw slicing technique. The moisture gradients measured by the Forstner bit layering technique were the highest and bandsaw slicing results were the lowest in all the moisture profile figures.

The bandsaw slicing results were low because the high temperature from the bandsaw during the slice cutting decreased the moisture content of each slice, and there was also a little moisture loss between the slice cutting and weighing procedure.

The Forstner bit results were high because there was some sawdust loss in drilling each layer from the block, and there was also some material loss during ovendrying each layer of wood removed. The air currents in the oven blew out some sawdust from the special containers. These material losses were considered as the moisture of each layer when calculating the moisture content of each layer of wood removed. So the moisture gradients obtained by the Forstner bit layering technique were higher than the real moisture gradients.

The flaking technique and razor blade slicing technique overcame the moisture loss and material loss problems. The knives were controlled by hand in both techniques when cutting the flakes and slices. There was no high speed cutting procedure. So no high temperature affected the moisture content of flakes and slices. Through weighing the blocks before and after each cutting, the moisture loss of each flake and slice caused by the environment was also controlled to some extent. So the results obtained by these two newly developed techniques were between the results obtained by the Forstner bit technique and bandsaw technique. It can be concluded that the moisture gradients measured by the two new techniques are more close to the true value than those measured by the two existing techniques.

Examining the correlation coefficients (R^2 value) for the moisture gradient regression lines obtained by the four techniques, the razor blade slicing and bandsaw slicing techniques have a higher R^2 value, and the Forstner bit layering technique had the lowest correlation coefficient. This meant that there was a higher variance in the results obtained by the Forstner bit layering technique and a lower variance in the results obtained by the razor blade slicing and bandsaw slicing techniques. Using the bandsaw to cut the slices caused no splits on the surface of the slice. Although there was kerf loss during the slice cutting, that didn't cause variance in the results of moisture gradients. The slices had good surfaces after being cut from the block. So the variance was small in the results. For the razor blade slicing technique, there were some small splits on the surfaces when cutting the slices, but preliminary tests proved that the material loss was not significant enough to affect the results in this method. When the block was dried, it became harder to cut smooth slices with the razor blade. So the variance in the moisture gradients measured by the razor blade slicing technique after 8 days kiln was a little higher than the earlier tests. The bandsaw slicing technique and razor blade slicing technique were very similar to each other. They were both fast and easy methods for measuring the moisture gradients. But bandsaw slicing had the kerf and moisture loss disadvantages. Razor blade slicing overcame these two disadvantages.

Forstner bit layering technique was also developed to overcome the two disadvantages of the bandsaw slicing technique----kerf loss and moisture loss. But the material loss had a significant effect on the moisture gradient results. The amount of material loss could not be controlled for each layer drilling, so the variance in the results would be much higher with this technique to measure the moisture gradients. The testing procedure with the Forstner bit layering was a little complicated and time consuming. And the thickness of each layer could not be too small in order to get enough wood removed for the significant weight change to calculate the moisture content.

Flaking technique could get thinner slices than the other techniques. The thinner the slices, the more detailed the moisture gradients could be determined, in turn, the more information would be available for the study of drying stress and strain. The moisture gradients are usually very steep near the surface during the first period of kiln drying. Steep moisture gradient is one of the factors causing the high drying stress and strain. So the more, clear knowledge of steep moisture gradient is very important to the stress-strain study. But the thinner the slices, the more the slices would need to be cut, so the flaking technique requires a little more time compared with the bandsaw and razor blade slicing techniques. The more moisture content data obtained from the flakes would inevitably bring a little more variance for the moisture profiles measured by the flaking technique compared with the less data obtained by the other techniques. For the flaking technique, the blocks were weighed before and after each slice cutting to decrease the moisture loss during the cutting and between the cutting and weighing of each flake. Although trying to weigh the blocks immediately after each cutting, there was still some environmental effects on the moisture content of the surface of the block, but which was not significant.

Comparing the two newly developed techniques ---- flaking technique and razor blade slicing technique, the results obtained from these two techniques were close to each other and more close to the true value than the other two existing techniques. Razor blade slicing technique is fast and easy to perform and had less variance in the results. It is appropriate for the practical use in the wood drying industries. Flaking technique is also an easy method and can obtain much thinner flakes without significant moisture or material loss. So it is more helpful to the drying research study because the moisture gradients obtained from it are very clear and detailed. But this technique is a little more complicated and time consuming.

3.2 Discussing the thickness effect on measuring the moisture gradients

In the Gorvade & Argenbright (1980) study of comparing the methods for preparing moisture gradient sections, they found the moisture content loss in cutting slices increased with decreasing slice thickness. So in this test, the two newly developed techniques for measuring the moisture gradients----flaking and razor blade slicing technique, which were also the better techniques as concluded from the first test----were used for testing the slice thickness effect on measuring the moisture gradients.

Three thickness series for the flaking test and three thickness series for the razor blade slicing test were chosen based on the requirements of the testing equipment. The flaking machine cannot cut flakes more than about 1.4mm thick. So a 0.6mm, 0.9mm and 1.2mm thickness series was chosen based on the suitability of adjusting the knife of the CAF flaking machine, and distinguishing the different thickness effects. Due to the wood structure it is difficult for the razor blade equipment to cut good slices thinner than a 2mm thick, so a 2mm, 2.5mm and 3mm thickness series was chosen to test the thickness effect by the razor blade slicing technique. As done in the first test, the moisture content obtained from each slice or flake was assumed to be the average moisture content and plotted at the center of each slice or flake in the moisture gradient graphs.

The six thickness series were tested at each of the five conditions----green condition, after 2 days, 4 days, 6 days, and 8 days kiln drying. Data and regression lines for each series are depicted in Figures 3.10-3.14. Cubic equations with correlation coefficients for each line are shown in Table 3.4.

From the original profile for the moisture content distribution in the block under the green condition as shown in Figure 3.15, there were 3 or 4 points with very high moisture contents near the two surfaces shown by the 0.6mm-thick flake result. The extra high moisture contents in these 3 or 4 flakes were caused by condensation on the surfaces. When putting the blocks in the plastic bags immediately after cutting from the board to prevent the moisture loss and waiting for the slice cutting, condensation occurred near the surfaces of the block, and when taking out the blocks from the plastic bag for cutting the flakes, the two surfaces quickly equilibrated with the environment and leaving the next 1 or 2 layers with high moisture contents. Condensation only occurred when the block had high moisture in it. And only if the flakes were very thin, could the condensation be tested and showed in the moisture gradient profiles. This phenomenon could also be seen in the 0.6mm- and 0.9mm-thick series moisture profiles after 2 days drying as shown in Figure 3.16. The extraordinary points of condensation affected correlation coefficients of the regression equations for the moisture gradients, so the regression of the data was performed after taking off these points as shown in Figure 3.10 and 3.11.

In the green condition, significant differences in R^2 values among the six thickness series were found, and R^2 values for the thinnest series were the lowest in the two groups. Only the 2.5mm-thick slice series test had a relatively acceptable R^2 value. This means that under the green condition, there was no strong correlation between the moisture contents and positions in the wood.

After 2 days kiln drying, the correlation coefficients were getting better for the six series thickness tests. The 1.2mm-thick series and 3mm-thick series had the highest R^2 values in the two groups. It can be concluded that for the relatively wet samples (during the first couple of days drying), the thinner the slices cut, the more the variances would be in the moisture gradients obtained. This is because with a relatively high moisture in it, the wood would be more susceptible to the environment.

With the drying continued, the variance in each thickness series was getting smaller as can be seen in the Table 3.4. All the correlation coefficients were becoming higher and higher for the moisture profiles obtained on 4 days, 6 days, and 8 days kiln drying and all the three series lines in each group were close to each other, especially for the flaking results. So it can be concluded that there is no significant thickness effect on measuring moisture gradients after 4 days drying for both flaking technique and razor blade slicing technique and the variance is also unaffected.

In the Gorvade & Argenbright's study data, they found there was a slice thickness effect on measuring the moisture gradients. That was because they used saws to cut slices and weighed the individual slices. Since the slices were thin and sensitive to the environment, the high temperature coming from the saw and the relative humidity of the environment would affect the moisture contents in the slices. So the thinner the slices, the more sensitive the slices to the environment, and the more decrease of the moisture content for each slice. But in this study, by weighing the blocks before and after each slice or flake cutting instead of weighing individual slices and flakes, the moisture loss of the slices and flakes would be eliminated. So there was not much thickness effect on measuring the moisture gradients by both techniques.

The 0.6mm thick flaking test had the highest correlation coefficient among the three series by the flaking technique after 4 days drying. However, under the green condition the 0.6mm thickness series data gave a very low correlation coefficient , this was because of the weak relationship between the moisture distribution and position under the green condition as it had been showed by all the thickness series testing results, not the technique effect or slice effect. And 0.6mm thickness result gave a much more real moisture profile showing condensation near the surface of the block as in Figure 3.15. Since there is no flake thickness effect on the moisture gradients measured with the flaking technique, and the thinner the flakes, the more detailed the moisture gradients could be determined, the help it would provide for the drying stress study as it had been concluded in the first test, so the 0.6mm flake thickness was the best for the flaking technique. For the razor blade slicing technique, which is better for the practical industry use as concluded in the first test, 3mm slice thickness is the best for industry quickly measuring moisture gradients during the production if there is no slice thickness effect on the results as it was just concluded in this second test.

Comparing R^2 values for the moisture gradients equations obtained after 6 and 8 days drying, all the three thickness groups by the flaking techniques had higher correlation coefficients than those of the three groups by the Razor blade slicing technique. In the testing procedure on those two days, it was felt that better flakes with smooth cutting and less splitting could be obtained, which means drying to a certain moisture content level---- below 50±5% general average moisture content, the flaking technique is the better for measuring moisture gradients in the wood. For the razor blade slicing technique, R^2 values for all the three thickness groups were becoming smaller with the drying time continued, which showed a trend that the drier the block became, the more the variances would be in the data of moisture gradients measured. But that was not a big significant change. During the test procedure with the razor blade on those days after 4, 6, and 8 days drying, more splits of the slices were found during cutting. The slices were becoming more difficult to cut with the razor blade when the samples were getting drier and drier.

So it can be concluded that flaking technique was becoming better for measuring the moisture gradients with the samples becoming dry. On the contrary, the razor blade slicing technique was becoming harder when the samples dried. This discovery was also demonstrated in the first test. The correlation coefficients for the flaking technique after 6 and 8 days drying were going up and for the razor blade slicing technique they were going down.

3.3 Comparing the moisture gradients in the radial and tangential directions

Drying stresses are usually caused by the two factors ---- moisture gradients and restrained shrinkage. A lot of research has been done on the water conductivity and shrinkage in the radial and tangential direction. (Barefoot 1963, Cloutier & Fortin 1993, Li & Plumb 1994, Shupe et al. 1995, Wu & Milota 1995). They all demonstrated that water conductivity and diffusion coefficients in the radial direction are constantly higher than in the tangential direction, and the tangential shrinkage was consistently greater than the radial shrinkage for all wood types.

Moisture gradients are considered dominant for the study of drying stresses. Drying degrades can be mainly ascribed to the drying stress resulting from the uneven shrinkage due to the moisture gradients. So the moisture gradients in radial and tangential direction were compared in this test.

While controlling the direction of moisture evaporation in the boards during the kiln drying, moisture gradients in the radial and tangential direction were measured by the flaking technique. The moisture profiles in these two directions measured on the five testing days are shown in Figures 3.17-3.21.

Under the green condition, the initial moisture content of the board for testing the moisture gradients in tangential direction was a little higher than that of the board for testing the moisture gradients in radial direction. This was because when cutting the two testing boards from the big quarter-sawn board, the two testing boards were cut side by side but not exactly separated along the axis of the quarter sawn board. The board for testing the moisture gradients in radial direction (Board R) was a little closer to the pith than the board for testing the tangential moisture gradients (Board T). So the initial moisture content for Board T was a little higher than that for Board R. The end faces of the two boards are shown in Figure 3.22.

After two days kiln drying, the moisture gradients in the two boards were generated and similar to each other. But the moisture profiles were not symmetrical as they usually are. This was because the growth rings were not flat but had a little curve as shown in Figure 3.22. The general average moisture content of Board T was a little lower than that of Board R. This could be because the moisture evaporated faster in the tangential direction than in the radial direction at the beginning of kiln drying, but more tests would be needed to prove this conclusion.

In the following few days of kiln drying, moisture gradients in the radial direction were all a little lower than those in the tangential direction, as shown in Figures 3.19-3.21. But the conditional error test showed that only on the 2-days drying and 4-days drying tests, the differences of the moisture gradients between the radial and tangential directions are statistically significant. On the 6-days drying and 8-days drying tests, the differences are not significant. And the difference between the radial and tangential moisture gradients on the 2-days drying test was caused by the unsymmetry of the profiles. So only on the 4-days drying, it can be concluded that the moisture moves faster in the radial direction than that moves in the tangential direction by this test.

Moisture moves faster in the radial direction than in the tangential direction is because the contribution of the rays to the radial permeability. For red oak, there are a lot of rays----uniseriate and multiple rays, within its structure.

From Figures 3.19-3.21, it could also be seen that the moisture gradients in the tangential direction were slightly steeper than the moisture gradients in the radial direction. The steeper the moisture gradients, the higher the drying stresses would be generated within the wood during drying. So the drying stress along the tangential direction could be higher than that along the radial direction as a result of the steeper moisture gradient in the tangential direction.

The very significant shrinkage along the tangential direction could also be seen in the Figures 3.19-3.21, but only a little shrinkage along the radial direction compared with the tangential shrinkage was found. And the tangential shrinkage began much earlier than the radial shrinkage. There are several anatomical factors that explain the higher shrinkage in the tangential direction than in the radial direction(Parshin & Zeeuw, 1980). First is because of the more transverse shrinkage in latewood less in earlywood. The tangential shrinkage is largely controlled by the latewood, which forces the earlywood to comply with it. The radial shrinkage is a summation of early wood and latewood shrinkage. It is smaller than the tangential shrinkage because of the presence of the low-shrinkage earlywood component. The second factor is the presence of rays which restrained the radial dimensional change. The third factor is the higher lignin content in radial walls than in the tangential walls, and shrinkage decreases with increased lignification.

The major defects when drying red oak boards are the surface checks. These are caused by the high drying stresses primarily in the tangential direction. When there is a high stress acting in a tangential direction, radial splits between cells will be formed with the fibers being separated by the tangential stresses.

Table 3.3 for the First test regression analysis. (PDF, 21K, table3-3.pdf)

Table 3.4 for the Second test regression analysis. (PDF, 24K, table3-4.pdf)

Figure 3.1--Figure 3.9 for the First test. (PDF, 204K, test1.pdf)

Figure 3.10--Figure 3.16 for the Second test. (PDF, 241K, test2.pdf)

Figure 3.17--Figure 3.21 for the Third test. (PDF, 114K, test3.pdf)

Figure 3-22 (PDF, 10K, fig3-22.pdf)