EFFECT OF AIR VELOCITY ON SURFACE MOISTURE CONTENT OF RED OAK AND SAMPLE GEOMETRY UPON ITS EMC

Kosasi Kadir and Robert Erickson
University of Minnesota
St. Paul, Minnesota

INTRODUCTION

Equilibrium moisture content (EMC) is an important physical property of wood. When wood attains a stable weight during exposure to air maintained at constant dry bulb temperature (dbt) and percent relative humidity (%RH), it has reached its EMC. Some factors that will affect the length of time required for a piece of wood to reach its EMC are its size (ratio of surface area to mass), grain orientation (end grain diffusion is comparatively rapid), air quality (dbt, %RH, and degree of air circulation), and the specific gravity of the wood (diffusion rate decreases as the specific gravity increases).

The USFS Wood Handbook is one source for EMC data. Generally speaking, published EMC tables do not give the specific test conditions used for obtaining the values nor do they identify the species used for the testing. It is well known that species effects do exist. For example, woods such as teak, honduras mahogany and California redwood all have heartwoods comparatively high in water-soluble-extractives. This gives them lower EMC values then for woods of comparable specific gravity and consequently they are well recognized for their dimensional stability.

In the use of hardwood kiln schedules it is generally assumed, to the authors' knowledge, that the surface moisture content (SMC) comes to an equilibrium state in keeping with the EMC of the circulating air. In order to minimize the potential for surface checking in the drying of oak species, air with a high EMC potential is circulated over the lumber in the early stages of drying. The higher the EMC, the less shrinkage and therefore the lower the tensile stress. This reduces the potential for checking and is a major principle applied not only in the drying of hardwood lumber, but is equally valid for much softwood lumber drying.

In light of known species differences, and possible effects of air factors upon EMC, it is legitimate to ask what SMC actually exists for oak lumber during its initial and most critical stage of kiln drying. In other words, how well do the available EMC data describe the situation for red oak lumber during kiln drying?

For example, quite often in the drying of oak lumber, surface checking can be a problem even though the recommended dbt and %RH for the initial step(s) of the schedule is (are) under precise control. In practice the recommendation is to reduce the air velocity (AV). However, to the authors' knowledge it is not reported in the literature exactly how this benefits the situation. Is the overall moisture content gradient changed? Is the SMC increased? Is there possibly a combination of the two occurring? Or is it strictly a matter of altering the overall moisture content profile?

RESEARCH OBJECTIVES

To determine the effect of:

1. Air velocity on the SMC and the MC profile in the drying of 4/4 red oak lumber.
2. Sample geometry upon the EMC of red oak.

EXPERIMENTAL MATERIALS AND PROCEDURES

Freshly sawn presurfaced 4/4 red oak boards were dried in a Blue M environmental chamber that was operated at a constant dbt of 110° F and a constant wet

temperature (wbt) of 105° F. (Published EMC of 16.2%) The equipment was able to maintain the dbt essentially constant while the wbt varied intermittently from its set point by about + 0.5° F.

Through a manipulation of special baffling and the cross sectional area available for air flow through the stack of stickered boards, it was possible to convert the fixed volume of air delivery in the working chamber to the three selected air velocities of 200, 600 and 1000 fpm. The stickered unit of boards was only one board wide and air velocities were measured on the leaving air side of the unit by use of a TSI Model 650 air flow meter. After the stickered unit was installed, the leaving air side of the unit was traversed with the probe of the meter to insure that uniform AV existed through the air flow channels coincidental with the sample (data collection) boards. The probe was then left in a fixed location on the leaving air side of the unit during the life of a given experimental run.

Three runs were conducted at each AV, with two sample boards (data boards) contained in each run. One of the boards was true quartersawn and the other was true flatsawn. Each data board was initially 21.5" long and planer surfaced two sides to a 1.0" thickness. Final board width was 8.0" following ripping and jointing of both edges.

Figure 1 illustrates the layout of 21 cross sections, each 0.75" along the grain, to be removed during drying. The parent cross sections removed at the 4th, 6th and 8th sampling periods each contained three of the 0.75" cross sections. The first cross section was an offcut (discarded), the second was for elastic strain analysis and the third was used to obtain MC data. For the remaining sampling times the parent cross section yielded just two 0.75" cross sections, the first being the offcut and the second for MC data.

When the parent cross section was removed from the data board, it was immediately wrapped in aluminum foil and then temporarily set aside. The data board was then "end coated" via application of a strip of fiber reinforced aluminum faced adhesive tape that was covered with a protective end plate made of 1/8" thick hardboard and attached with two short nails. Once end coated, the data board was reinstalled in the Blue M along with the required lengths of dummy boards to replace the portions of data board removed. The use of the dummy boards was required in order to maintain the desired AV through the stickered unit. Processing time for the data board was a matter of just a few minutes since the bandsaw and all other required equipment were concentrated near the Blue M.

Figure 2 illustrates subdivision of the MC cross section. Subsection C provided SMC data via microtoming of both the top and bottom faces and subsection B yielded MC data for the overall MC profile. Subsections A and D were discarded.

Subsection B was immediately wrapped in aluminum foil and then temporarily set aside while subsection C was rotary microtomed in a walk-in environment room maintained at 60° F and 70% RH. This EMC condition of 13%, plus the speed of processing, nearly eliminated changes in MC of the microtome slices during their production. The time to produce eight microtome slices and put them into their pre-weighed container was about 15 to 20 seconds and the total time for microtoming 40 slices from one face was about two minutes. Through an evaluation of weight loss as a function of exposure time for unprotected microtome slices, it was estimated that the slices lost about 1.0% of their green weight during their collection. Since each microtome slice was 50 microns thick, a total thickness of about 0.08" was removed from each face of subsection C.

The 40 slices from a given face were placed into preformed, preweighed aluminum foil containers as follows: four slices into each of containers 1 and 2 and eight slices into each of containers 3 through 6. Slices for a given container were produced, immediately collected by tweezers and placed in the container, and then the container was sealed by crimping and rolling the perimeter of the open end.

Individual containers were then weighed to the nearest 0.0001 gram prior to ovendrying. To facilitate the ovendrying, which was at 220° F for a period of at least 24

hours, the foil containers were perforated with an ordinary stick pin.

Ovendry weights were determined after the containers had been cooled in a desiccator containing silica gel. The original tare weights of the containers, and their tare weights following ovendrying, were determined to the nearest 0.0001 gram.

Subsection B was subdivided by using a 1/16" kerf bandsaw, resulting in eight slices with an actual thickness for each of about 0.07". Slice MCs were determined by the standard ovendrying method with close attention given to minimizing experimental error in all steps of the processing.

Total elastic strain data were collected after two, four and ten days of drying. A slice 1/8" thick, with its length equal to full board width, was bandsawed from both top and bottom side grain surfaces of the cross section. Following removal they were wrapped in foil and allowed to "relax" for about 45 minutes since it was determined that elastic strain slices of this type need that length of time to achieve their relaxed and presumably stress-free length. The total elastic strain was equal to the length of the slice prior to removal from the cross section, minus its length following removal and complete relaxation. Elastic strain was determined for only the surface slices since this was considered of greatest interest in the context of investigating the possible effect of AV upon SMC.

The EMC samples were obtained from 10" long parent pieces that were end matched to the 20.5" long AV data boards. Figure 3 shows the types of samples and how they were obtained. One set of samples was used to determine EMC values for desorption from the green condition and the second set was for determining EMC values for adsorption from the ovendry condition. The microtome slices were again 50 microns thick and they were concentrated into a perforated foil container. Cross sections were individually suspended in the environmental chamber by use of thin copper wire.

The EMC testing was done in the Blue M unit at the same dbt and %RH as for the drying experiments but the AV was 500 fpm. A dry bulb/wet bulb hygrometer was placed in the working chamber in order to confirm the temperatures tracked on the Blue M chart recorder. (This same confirmation technique was utilized in the AV experiments.)

The EMC samples were weighed each day to the nearest 0.0001 gram. Weighings were continued for the microtome slices and the 1/8" and 1/4" cross sections for 24 days. Weighings were continued 49 days for the thicker cross sections.

To check for true equilibrium, a linear regression of MC on time was done for each sample type for both adsorption and desorption. For microtome slices and the 1/8" and 1/4" cross sections the time span of 5 through 24 days was employed, and for the larger cross sections the time span was 27 days through 49 days. These time spans were selected since within them the sample weights appeared to have stabilized.

RESULTS AND DISCUSSION

Surface Moisture Content

Surface MCs as a function of AV and drying time are given in Figure 4. Surface MC is the average MC of the first four microtome slices from the top and bottom faces of the drying board. Data from the top and bottom faces could be combined since it was determined that the two faces had equivalent drying behaviors. It should be kept in mind that four microtome slices of 2000 microns thickness each, is a total thickness of about 0.008". The authors take the liberty of speaking about the MC for a thickness of less than one-hundredth of an inch as a "surface MC".

The initial SMCs (zero drying time) were about 65% for all three AVs. These initial SMCs compared to overall initial average board MCs in the range of 80 to 85%. The difference reflects primarily a reduction in SMC during storage of the sample boards in the coldroom. However, these differences are not considered of great consequence since the starting SMCs still adequately represent green, freshly harvested wood.

Differences in SMC were developed by four hours of drying and these differences reached a maximum by ten hours of drying. At one day of drying the respective AVs had apparently adjusted their heat and mass transfer rates to desired levels. The authority for this statement comes from the fact that the MC differentials in effect at one day remained nearly constant for the next four sampling periods, i.e. through the ten days of drying. The constancy of differentials is illustrated in Table 1. During the nine-day period day one through day 10, the average SMCs for 200, 600 and 1000 fpm are, respectively, 17.2, 16.0 and 14.2%. At one day the analogous values were 20.4, 18.9 and 17.0% while at ten days they were 15.0, 13.5 and 17.3%. A comprehensive comparison of these differentials supports the conclusion that they did not significantly change during the nine-day period.

Table 1. Percent MC values of the first-four microtome slices as a function of drying time.

Time (Hours)	200 fpm	600 fpm	1000 fpm
4	33.8	29.6	28.4
10	29.0	23.6	20.3
16	24.5	21.0	18.7
24	20.4	18.9	17.0
48	18.7	17.1	15.8
96	16.4	15.6	13.7
168	15.4	14.7	12.9
240	15.0	13.5	11.6
Average MC	21.7	19.3	17.3

The differentials in SMC remained constant during the nine-day period even though the absolute SMC for all three AVs steadily decreased. The decrease in SMC from one day through ten days of drying was remarkably uniform for the three AVs, i.e. 5.4%. One interpretation of this is that surface phenomena were very much in control of the overall drying with little influence from interior phenomena. A given AV probably established a specific heat and mass transfer at the surface that resulted in an accordant SMC. For each AV the heat and mass transfer for the board decreased in correspondence with its decrease in average MC. As time progressed this produced a progressively lower SMC for all three AVs. Since the SMCs dropped an identical amount for the three AVs it seems to indicate that surface phenomena "were in charge" so to speak. (Subsequently the matter of overall MC profiles will be discussed.)

It is generally assumed that the surfaces of drying boards come to a MC in equilibrium with the EMC of the surrounding air. When oak lumber is kiln dried from the green condition there may be a period of perhaps ten days in which the kiln dbt and wbt are comparable to those used in this study. (Of course, the AV will probably be somewhere around 400 to 500 fpm.) However, it is apparently in error to assume that the SMC for the oak lumber will be at the predicted 16 to 17%. As shown in Figure 4, at five days of drying the SMCs for all three AVs were below the expected EMC value of 16.2%. At 10 days of drying the SMC for 1000 fpm was nearly 5% below the expected. It seems apparent that water molecules in the circulating air are not capable of transferring to the lumber surface in an efficient enough manner to keep the wood at the predicted EMC, which in this case is 16.2%.

Why didn't the SMC remain at the EMC of the circulating air? As discussed earlier, the change in heat and mass transfer phenomena at the surface is believed to have been very influential. A second contributing factor may have been the stress condition at the board surface. During the entire 10-day period the board surfaces were stressed in tension. As discussed in the literature, wood subjected to tensile stress during desorption will attain a lower EMC than if not stressed. Perhaps the SMC being lower than the predicted EMC was due in part to the tension stress. Unfortunately the drying

was discontinued at approximately stress reversal. If analysis had been continued, it may have been possible to determine if the change from tensile to compressive stress at the surface would have altered the SMC picture that was in effect at 10 days of drying.

Moisture Content Profiles

In Figure 5 are shown the overall MC profiles at one day and 10 days of drying for the three AVs. At just one day the concavity of the near-surface profile to the MC axis for 200 fpm is clearly evident and it is still in effect at 10 days of drying. A comparable concavity never did exist for the 600 and 1000 fpm AVs.

The effect of AV upon average MC at mid-thickness (core) of the board is evident after just one day of drying. Since the 21.5" long sample boards for the three different AVs were end matched and obtained from the same 8' long parent boards, the differences in core MCs shown in Figure 5 are undoubtedly due to a real effect of AV rather than random variation. It is therefore somewhat surprising that a difference in core MC of several percent for 200 and 1000 fpm should develop as early as one day. Is this differential the result of unequal rates of free water movement due to capillary forces? Arguing against such a conclusion is the fact that at 10 days of drying the same order of core MC differentials remained in effect even though very little free water remained. Also if free water flow and AV were interacting such that the higher the AV, the greater the free water flow, then it seems there should have been progressive increases in the differentials in core MCs with drying time. This does not appear to be the case. Figure 6, which gives the MC profiles for the seven day "intermediate" stage of drying, shows basically the same scenario as those for one and 10 days of drying. This implies there was no mass flow of free water during this 10 day period of drying at constant 110° dbt and 105° F wbt.

One might ask, is it reasonable to expect the so-called free water to move in mass as a liquid? It is a well-known fact that thousands of psi pressure are required to squeeze the MC of green wood down to a value of perhaps 50 to 60 percent on an ovendry basis. Just how capable of liquid flow is such "free water"?

In light of these considerations, it seems more reasonable to conclude that the MC profiles displayed in Figures 5 and 6 result from a different thermodynamic system for each AV, and that the point of control for each AV is at the immediate surface of the board. The concept of possible "surface control" raises an interesting point for speculation. As discussed earlier, the differentials in surface MCs that became established by one day of drying remained in effect during the next nine days. Might then the use of low AV during the first day of drying establish a "high" surface MC that could be retained during the subsequent use of elevated AVs such as 1000 fpm? If these were reality, the precise manipulation of AV in the early stages of oak drying could prove quite advantageous. Establishment of the higher surface MC would reduce shrinkage and the tendency for surface checking, while an accelerated drying rate would result from the high AV. Another consideration is that the higher the MC at which the surface is maintained, the more efficient should be the heat transfer from the moving air stream to the surfaces of the lumber. If the surface is in fact the critical control point in oak drying, then some further investigation seems in order.

Drying Rates

Table 2 compared drying rates for the flatsawn and quartersawn boards by AV. In accordance with the well known phenomenon, the flatsawn boards dried faster than the quartersawn. The rates for both board types increased with AV but the greatest differentials were for the increase from 200 to 600 fpm. The average drying rate for 600 fpm was about 14% greater than that for 200 fpm. The drying rates were statistically different by AV at the 1% level of significance and by board type at the 10% level.

Table 2. Average drying rate in %MC/hour for the drying samples.

Boards	200 fpm	600 fpm	1000 fpm
Flatsawn	0.221	0.253	0.260
Quartersawn	0.205	0.230	0.235
Average	0.213	0.242	0.247
Ratio F/Q	1.078	1.100	1.106

Elastic Strain

Figure 7 gives total elastic strain as a function of average MC for the three AVs. Maximum tensile strain occurred with the AV of 1000 fpm. This is not surprising for that AV also produced the lowest surface MC, which in return translates into the greatest shrinkage. Stress reversal also occurred first with the 1000 fpm AV and it appears that the latest stress reversal would have occurred with the 200 fpm AV. The explanation for the relationship of stress reversal to average MC for the three AVs must reside in the different MC profiles exemplified in Figures 5 and 6. Differences in the MC profiles should translate into differences in distribution of drying stresses.

EMC Values

Table 3 summarizes EMC values for the samples of different geometry during desorption and adsorption. During desorption there was a consistent direct relationship between sample size and EMC. The microtome slices gave the lowest EMC and the 2" cross sections had the highest EMC. For adsorption there was an apparent trend for the EMC and the sample size to be inversely related but it was not totally consistent since the microtome slices show a lower EMC then do all of the cross sections and the EMC for the 1/2" cross section is noticeably out of sequence.

Table 3. The average desorption and adsorption EMC values for samples of different geometry.

Sample Geometry	Adsorption	Desorption	Adsorption/Desorption
Slices	10.03	9.41	1.07
1 x 2 x 1/8"	10.59	10.67	0.99
1 x 2 x 1/4"	10.44	11.44	0.91
1 x 2 x 1/2"	10.62	11.95	0.89
1 x 2 x 1"	10.39	12.82	0.81
1 x 2 x 2"	10.25	13.44	0.76

The ratio of adsorption to desorption MCs shows an interesting feature. The thinnest cross section (1/8") has a value of 0.99. This suggests that this cross section was approaching a size for which no hysteresis effect would have been demonstrated. This seems to raise a crucial question in regard to the hysteresis effect and how it is determined. Is hysteresis for wood simply a size phenomenon? It certainly seems to be the case for these red oak samples. If it is a size phenomenon, what is the explanation? The most plausible explanation seems to be the possible relationship between sample size and stresses that accompany dimensional change. The literature contains a number of papers that relate the application of external force to both adsorption and desorption EMCs. Also, theories have been advanced that wood hysteresis is due to the fact that wood is not perfectly elastic, i.e., it is subject to internal stress during MC changes. Such theories have also been supported by mathematical analysis. Intuitively it seems to make sense that the larger the cross section the greater the internal stress during drying. Consequently, during desorption there could occur an "entrapment" of water molecules in the cell walls due to the shrinkage-induced stress. Presumably, the thinner the cross section, the lower this stress is during both adsorption and desorption. Consequently,

with an essential absence of internal stress the 1/8" cross sections equilibrated to almost the same EMC during adsorption as during desorption.

The slopes of the regression lines for both the adsorption and desorption cross sections were determined to be not statistically significant. Consequently it was concluded that the cross sections had attained equilibrium. However, it was interesting that eight of the ten desorbing cross sections had negative slopes and all ten of the adsorbing cross sections had positive slopes. This suggests that both desorbing and adsorbing samples were still seeking a more precise, "true" equilibrium in spite of exposure times of 24 and 49 days. This prompts a visualization of the cell walls possessing a cell wall relaxation mechanism of very extended duration. If true, it then seems reasonable to suppose that the time duration required for a given sample to attain "true" equilibrium would be temperature dependent. The higher the energy state the more quickly should be achieved the desired state of relaxation for the wood cells.

Also of interest was the fact that the slopes of the regression lines for both desorption and adsorption microtome slices were all positive and statistically significant at the 5% level. This implies that the desorption slices "overshot" their desired EMC and then commenced a time-dependent readsorption toward "true" equilibrium. If this is a real effect it is difficult to explain why it exists. Certainly additional research is necessary to either confirm or refute this phenomenon. The positive slope of regression lines for adsorption microtome slices is more readily acceptable. It would seem to indicate that the ovendried microtome slices are still "chasing" a desired equilibrium weight. What is surprising is that such a long term time horizon exists for ultra thin slices of wood with an extremely high surface area to mass ratio. This may indicate that the suggested relaxation phenomenon does exist at the cellular level but will manifest itself in a rate and manner that is dependent upon the size and other attributes of a piece of wood.

CONCLUSIONS

Air velocity had a significant effect upon the surface moisture content of presurfaced red oak boards during drying from the green state down to about 30% moisture content at constant drying conditions of 110° F dbt and 105° F wbt. The higher the air velocity the lower the surface moisture content. Differentials in surface moisture that were established at one day of drying remained essentially constant during the next nine days of drying. This occurred while the surface moisture contents for all three air velocities of 200, 600 and 1000 fpm dropped an identical amount of 5.4% moisture content during the nine day period.

Surface moisture contents never stabilized at the 16.2% moisture content predicted from the equilibrium moisture content potential of the circulating air. After 10 days of drying the surface moisture contents for 200, 600 and 1000 fpm were, respectively, 15.0, 13.5 and 11.6%. It is apparently in error to assume that surface moisture contents in kiln drying are solely a function of the air's EMC potential and independent of air velocity and possibly other factors such as drying stresses.

The air velocity of 200 fpm produced a moisture content profile significantly different from those for 600 and 1000 fpm. Its unique profile offers an explanation as to why reductions of air velocity in commercial drying practice will mitigate an existing problem with surface checking. The 200 fpm air velocity resulted in a drying rate of 14% less than that for 600 fpm. Consequently, the use of reduced air velocities in commercial drying will probably also correlate with slightly reduced drying rates.

Equilibrium moisture content is affected by sample size. During desorption from their original green state it was found that the thicker the cross section the higher its equilibrium moisture content. During adsorption the reverse appeared to be true in which the thicker the cross section, the lower its equilibrium moisture content. The thinner the cross section, the smaller the hysteresis effect. For cross sections 1/8" along the grain, the ratio of adsorption to desorption equilibrium moisture contents was 0.99

and for cross sections 2.0" along the grain it was 0.76. It is concluded that the hysteresis effect for wood is dependent upon sample size and geometry and the associated internal stresses that occur during adsorption and desorption.

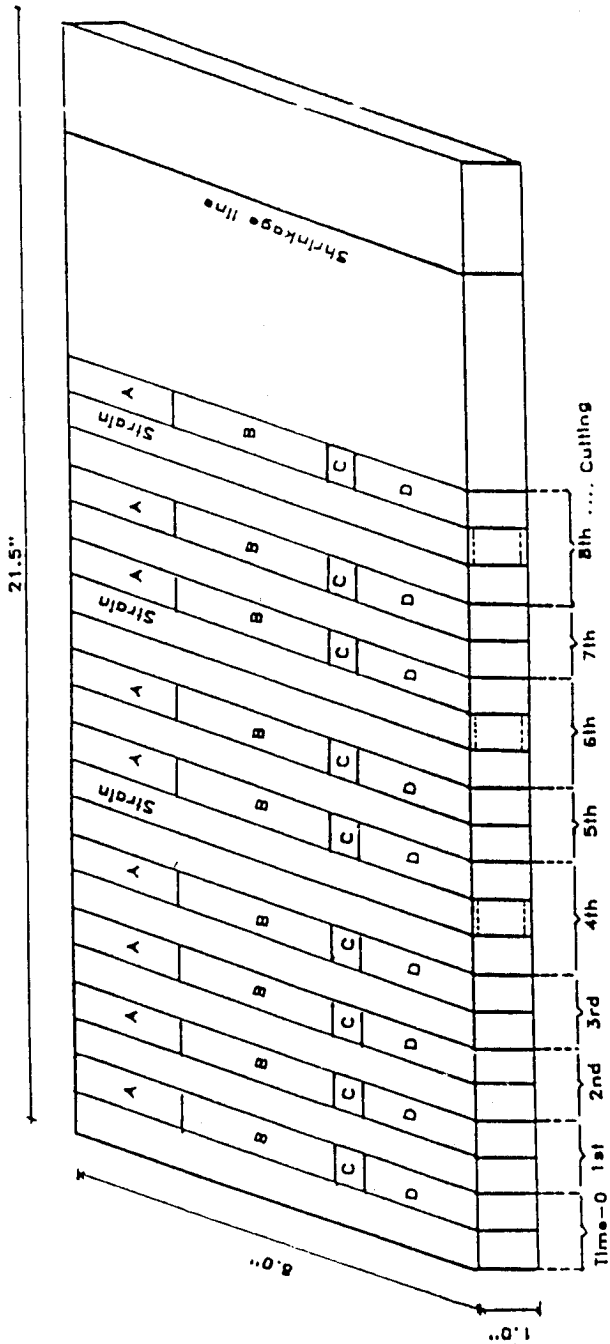

Figure 1. Illustration of how cross-sections were periodically removed from the drying sample. The cross-sections without designation were offcuts that were discarded. Cross-sections for determining total elastic strain were taken at the 4th, 6th and 8th cuttings. Figure 2 describes the utilization of the sections labeled A, B, C and D.

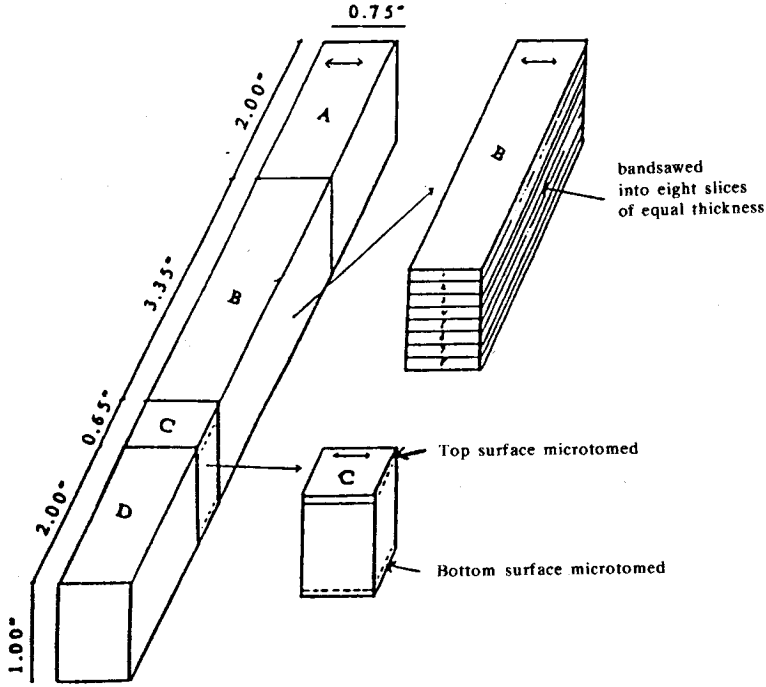

Figure 2. Illustration of how the MC cross-sections were sampled for evaluating Surface MC and Near-Surface MC profiles (C) and Gross MC profiles (B). A and D designate discarded offcuts.

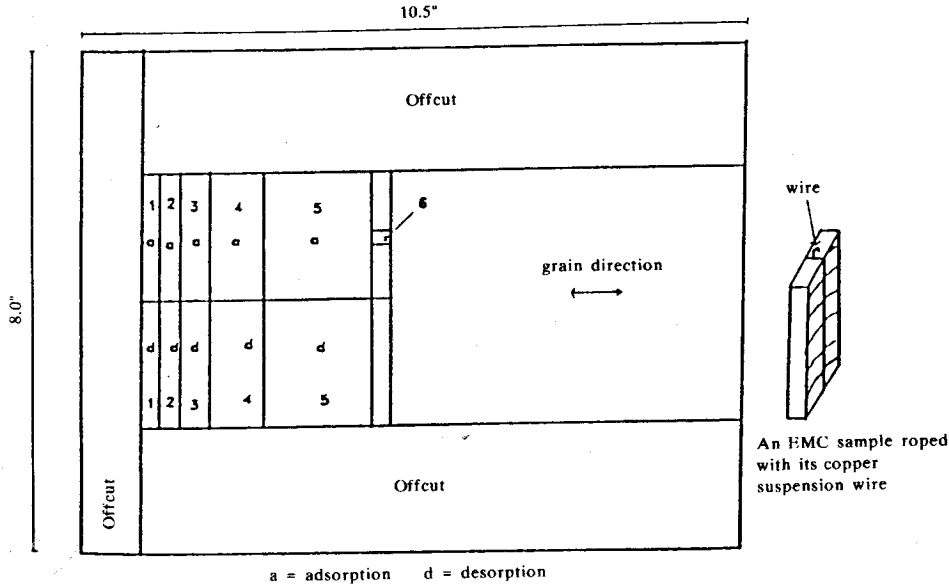

Figure 3. Top view of how EMC samples were obtained. The numbered cross sections were dimensioned as follows: #1 (1" x 2" x 1/8"), #2 (1" x 2" x 1/4"), #3 (1" x 2" x 1/2"), #4 (1" x 2" x 1") and #5 (1" x 2" x 2"). The small section #6 (0.65" x 0.75" x 1") was used for obtaining microtome slices for both adsorption and desorption samples.

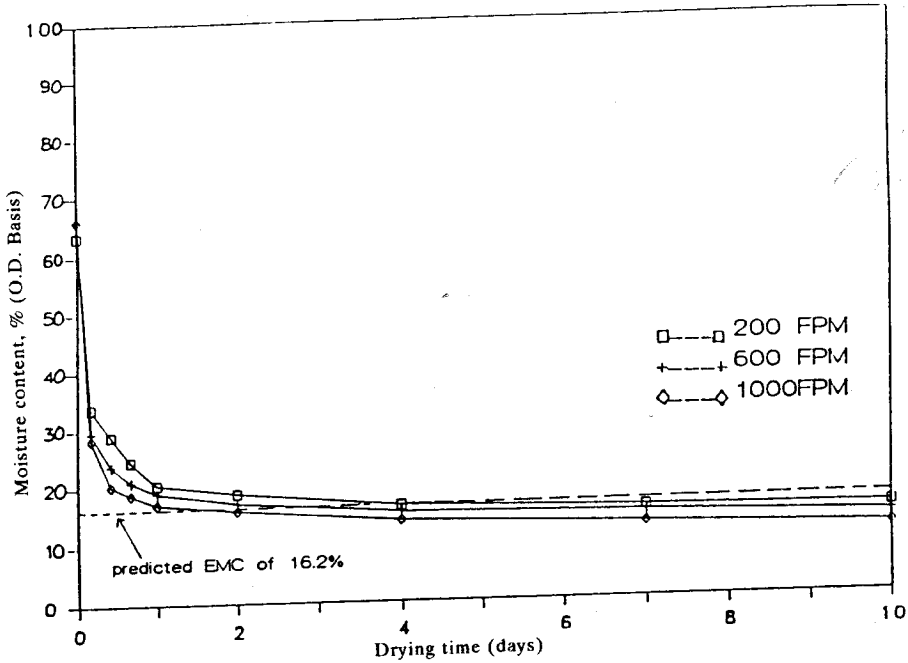

Figure 4. Surface MC as a function of drying time and air velocity.

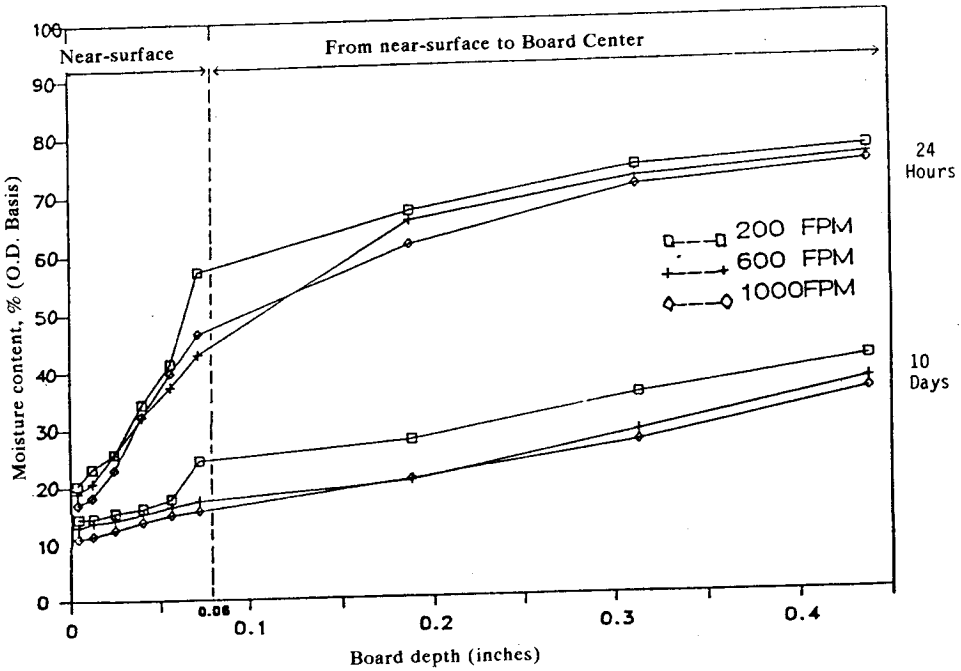

Figure 5. Overall moisture content profiles as a function of air velocity at 24 hours (top set of lines) and ten days (bottom set of lines).

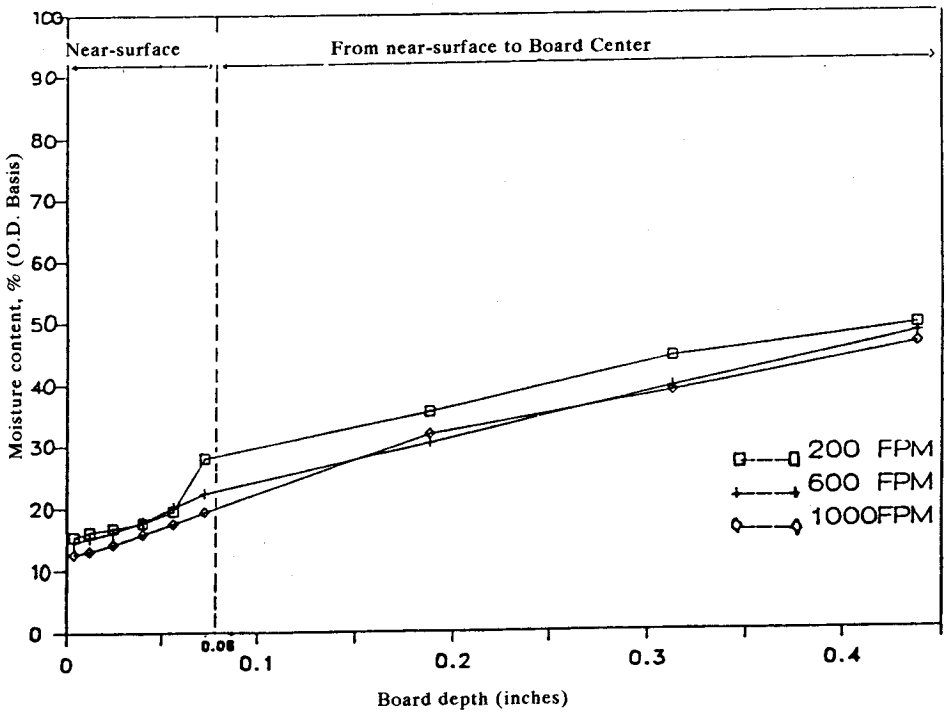

Figure 6. Overall moisture content profiles as a function of air velocity at seven days of drying time.

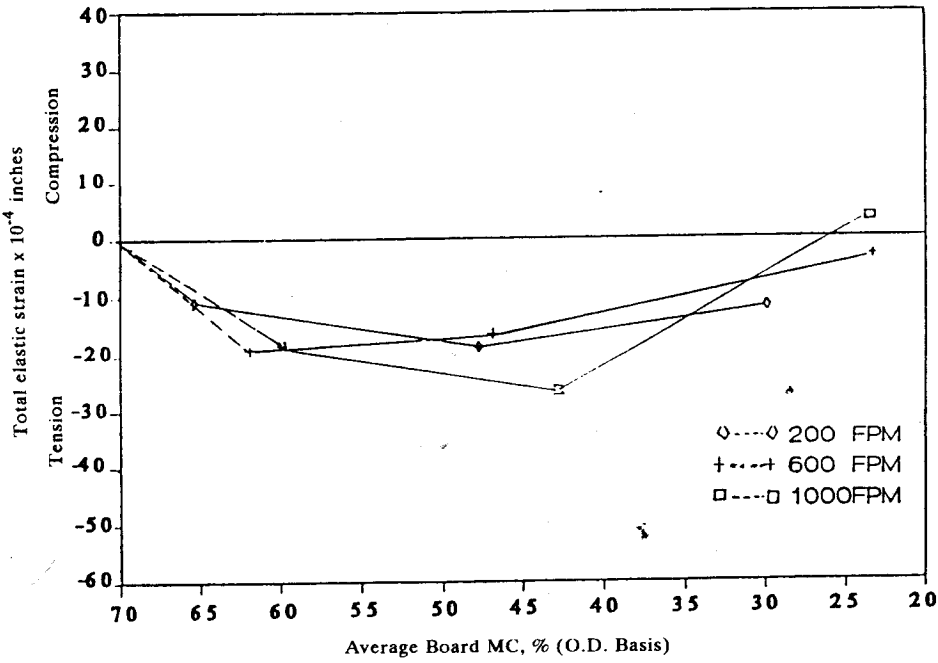

Figure 7. Total elastic strain for 8-inches wide red oak boards at 24, 96 and 240 hours of drying.