Time, Costs, and Energy Consumption for Drying Red Oak Lumber as Affected by Thickness and Thickness Variation

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Abstract

The time required to kiln-dry lumber is influenced by its thickness. Thicker material dries more slowly, and an increase in drying time increases energy consumption and drying costs. The purpose of the study was to analyze the effect of thickness variation — of the size that would be encountered by sawing variation — on drying time, costs, and energy consumption in kiln-drying 4/4 to 8/4 red oak lumber. The basis of the study is empirical drying rate data of red oak as a function of temperature, RH, and thickness. This data was generalized into an analytical function to allow estimates of drying rate to be calculated at any combination of the three variables. The analysis showed that even the small difference in thickness variation that would be encountered by sawing variation can have a significant effect on drying time. A 3/32-inch difference results in differences in drying time of 10 to 15 percent for 4/4 red oak lumber. The differences range down to 6 percent for thicker lumber. Differences in energy consumption range from 3 to 6 percent for the 3/32- to 4/32-inch thickness differences between minimum, target, and maximum thicknesses. Total drying costs are dependent upon specific operations, but if, as a first approximation, drying costs are assumed to be proportional to drying time, then differences in total drying costs due to thickness variations are the same, on a percent basis, as differences in drying time.

Method of Estimating Drying Time

Previous studies have described an experimental and analytical technique that resulted in a method of estimating the drying time of lumber from a commercial red oak group as a function of temperature, relative humidity (RH), and thickness (9,10). Drying rate was established experimentally at several different levels of each variable, and an empirical relationship was developed to describe drying time as a function of the variables. The basic assumption in establishing the empirical relationship is that drying rate is proportional to average moisture content (MC):

\[ \frac{d\bar{W}}{d\theta} = K\bar{W} \]

where \( \bar{W} \) = average MC at time \( \theta \) and \( K \) is a constant of proportionality

Carrying through the analysis, the unaccomplished MC change \( E \) is (9):

\[ E = b \sqrt{n} \frac{W_e - W_i}{W_e} \]

where \( W_e \) = equilibrium MC (%)
\( W_i \) = initial MC (%)
\( b \) = empirically determined coefficient for red oak
\( \theta \) = time (days)
\( l \) = board thickness (in.)
\( n \) = empirically determined thickness coefficient

The coefficient \( b \) describes the effect of temperature and RH on drying rate. Within the normal range of temperatures used in hardwood kiln schedules, \( b \) was found from thickness variation in sawing, drying time will also be affected. Undersize, target, and oversize lumber will dry at different rates. Oversize lumber will require longer drying time than target or thinner lumber, and drying costs and energy consumption in kiln-drying will also be greater.

IT IS GENERALLY KNOWN in the lumber industry that the drying time of lumber increases with thickness. It is also recognized that the increase in drying time exceeds a one-to-one relationship with thickness; that is, doubling thickness more than doubles drying time. In a survey of 100 circular sawmills, Telford (8) found only two that could keep the sawing variation of 4/4 lumber within a range of 1/4 inch. Reineke (7) found thickness variations of up to 3/8 inch in circular sawmills. In another study 37 percent of the lumber sampled was mismanufactured (1). In addition to possible volume loss due to thickness variation in sawing, drying time will also be affected. Undersize, target, and oversize lumber will dry at different rates. Oversize lumber will require longer drying time than target or thinner lumber, and drying costs and energy consumption in kiln-drying will also be greater.

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to be very nearly linear with the vapor pressure of water, and can be estimated by:

\[ b = 0.0575 + 0.00142 \rho \]

where \( \rho \) = vapor pressure of water (mm Hg), which can be related to temperature (within the range of 110° to 180°F) by:

\[ \rho = \exp \left( \frac{20.41 - 5132}{T} \right) \]

where \( T \) is in degrees Kelvin.

The thickness coefficient \( n \) is of particular interest here to analyze the effect of thickness variation on the time, costs, and energy consumption required in kiln-drying. If the only mechanism involved in lumber drying were diffusion, drying could be theoretically described as follows (2):

\[
E = \frac{8}{\pi^2} \left[ \exp(-\pi^2a^2D/4\ell^2) + \frac{1}{9} \exp(-9\pi^2a^2D/4\ell^2) + \frac{1}{25} \exp(-25\pi^2a^2D/4\ell^2) + \cdots \right]
\]

where \( D = \) diffusion coefficient and \( a, \ell, \) and 2 are as before. Note that the thickness coefficient \( n \) is 2. Even though lumber drying is generally diffusion controlled, there are several complicating mechanisms that prevent the literal use of Equation [2]. Internal flow of liquid water and boundary conditions (surface emission) are perhaps the two most severely limiting factors. One result of these complicating factors is that the thickness coefficient \( n \) is less than 2.

Kollmann and Côté (3) cite several studies that have shown thickness coefficients for lumber (not veneer) to vary between 1.25 and 1.7. The results of earlier studies (9) related to the present analysis were that for northern red oak lumber \( n = 1.52 \).

With estimates of \( b \) and \( n \), Equation [1] can be put in a more useful form to estimate the drying time of northern red oak lumber at each step in a kiln schedule:

\[
\tilde{t} = -a \cdot \frac{\ell^{1.52}}{b} \cdot \frac{1}{Y_o - Y_e} \cdot \frac{1}{W_o - W_e}
\]

where \( \tilde{t} = \) drying time (days)

\( a = \) empirical coefficient dependent on temperature and RH

\( \ell = \) board thickness (in.)

\( b = \) empirical coefficient dependent on temperature and RH

\( W_o = \) average MC at time B (%)

\( W_e = \) EMC conditions in kiln (%)

\( = \) initial MC (%)

### Drying Time

**Effect of Thickness**

Common nominal thicknesses of oak lumber are 4/4, 5/4, 6/4, and 8/4 which, in terms of rough, green lumber dimensions, correspond to 1-5/32, 1-7/16, 1-11/16, and 2-1/4 inches, respectively. Red oak lumber is sometimes kiln-dried from the green condition (approximately 80% MC), and quite often undergoes varying amounts (times) of air-drying before entering the kiln. Kiln schedules probably vary somewhat among operators, but the schedules recommended by the Forest Products Laboratory (6) can be considered representative of those used commercially. Schedule T4-D2 is recommended for 4/4, 5/4, and 6/4 red oak lumber and T3-D1 for 8/4 red oak.

Using Equation [3] and schedules T4-D2 and T3-D1, one can estimate kiln-drying time for red oak lumber for different thicknesses and from different initial MCs. The step-wise and total kiln-drying times of 4/4, 5/4, and 6/4 red oak (schedule T4-D2) from initial MCs of 80, 50, and 30 percent are listed in Table 1, and for 8/4 (schedule T3-D1) in Table 2. Overall views of the relationship of drying time, thickness, and initial MC are shown in Figure 1. The range of drying times is, of course, quite variable, from a low of 6.6 days required to kiln-dry 4/4 from 30 to 7 percent MC, to a high of 55.7 days required to kiln-dry 8/4 from 80 to 7 percent MC.

### Effect of Thickness Variation

Based on the estimates in Figure 1, a thickness change of 1/8 inch can change drying time by 10 to 15 percent. The general range of thickness variation in sawing is 1/8 inch, and a 10 to 15 percent change in drying time could be significant. Oak lumber is graded under the National Hardwood Lumber Association grading rules. Lunstrum (4) has listed thickness standards for lumber produced by circular headrigs under these rules. The difference in thickness between the stipulated minimum and the recommended maximum is 3/16 inch for 4/4, 5/4, and 6/4 lumber, and 1/4 inch for 8/4 lumber.
Figure 1. - Kiln-drying time of nominal lumber dried 4-4 schedules T4-D2 and T3-D1 (6) as a function of thickness and initial MC.

<table>
<thead>
<tr>
<th>Initial minimum thickness (%)</th>
<th>Final thickness (%)</th>
<th>Minimum thickness (in.)</th>
<th>Target thickness (in.)</th>
<th>Maximum thickness (in.)</th>
<th>4/4</th>
<th>5/4</th>
<th>6/4</th>
<th>8/4</th>
</tr>
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<tr>
<td>80</td>
<td>7</td>
<td>16.2</td>
<td>18.6</td>
<td>20.8</td>
<td>23.1</td>
<td>25.9</td>
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<td>50</td>
<td>7</td>
<td>11.6</td>
<td>13.2</td>
<td>14.8</td>
<td>16.4</td>
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<td>7</td>
<td>6.0</td>
<td>6.6</td>
<td>7.2</td>
<td>8.4</td>
<td>9.2</td>
<td>10.2</td>
<td>10.8</td>
</tr>
</tbody>
</table>

a) Dried by T4-D2 b) Dried by T3-D1 c) From (4).

Costs and Energy Consumption

Thickness Variation and Kiln Operating Costs

A number of elements make up the cost of kiln-drying lumber. Labor, energy, maintenance, depreciation, interest on inventory, drying degrade, land and building expense, insurance, and miscellaneous supplies are some of the major categories. While total kiln-drying costs vary from operation to operation, they can be considered in terms of cost per day per 1,000 board feet, as shown in Figure 3 for 4/4 lumber, where total kiln costs per thousand board feet are shown as a function of kiln cost/day/Mfbm, initial MC in the kiln, nominal thickness, and thickness variation. The assumption is made that kiln costs per thousand board feet rise linearly with kiln-residence time. Figure 3 shows that thickness variation can have a substantial effect on kiln-drying costs. For example, if 4/4 red oak lumber were kiln-dried from 50 to 7 percent MC in a kiln where the costs were $3/day/Mfbm, it would cost $39.30/Mfbm to dry at the target thickness and $44.40/Mfbm to dry at the maximum recommended thickness. The estimated percent increases in drying costs from minimum stipulated to maximum recommended thickness, and from target to maximum thickness, are the same as the percent increases in drying time. Thus, the graphs of Figure 2 represent percent increases in both drying time and drying costs.

Lost kiln-drying opportunity is also an element of total drying costs. If, for example, we compare kiln-drying target and maximum thickness 4/4 lumber between 50 and 7 percent MC the lost kiln capacity is significant. Maximum thickness lumber requires 1.6 days longer drying time than target thickness. With the approximate 2 weeks’ total drying time, this difference adds up to three lost kiln runs per year by not being able to control thickness variation in sawing within 3/32 inch.

Thicknes Variation and Energy Consumption

The variation in kiln-drying time with variations in thickness will cause energy requirements in the kiln to vary also, mainly because of the differences in time over which heat losses can occur. A material and energy balance analysis was conducted for drying red oak lumber under the same conditions and variables as before. All energy demands - lumber and structure heat-up, heat of evaporation, vent losses, conductive heat losses, and fan energy - were considered. The computer model assumed that the kiln was located at Madison, Wisconsin, had a 40-Mfbm capacity, contained six 1.5-hp fan motors, and all external surfaces had an overall heat transfer coefficient of 0.25 Btu per hour per square foot per °F.

An annual average of all energy consumption was used to account for changing ambient temperatures and
Table 4. Differences in energy consumption range from a low of 100,000 Btu/Mfbm between target and maximum thickness for 4/4 lumber kiln-dried from 30 to 7 percent MC to a high RHs, and thus heat losses. Total energy consumption in kiln-drying minimum, target, and maximum thicknesses of 4/4, 5/4, 6/4, and 8/4 lumber dried from 80, 50, and 30 to 7 percent MC are shown in Table 4. Differences in energy consumption range from a low of 100,000 Btu/Mfbm between target and maximum thickness for 4/4 lumber kiln-dried from 30 to 7 percent MC to a high

<table>
<thead>
<tr>
<th>Initial minimum MC in kiln (%)</th>
<th>Final target MC in kiln (%)</th>
<th>4/4&quot;</th>
<th>5/4&quot;</th>
<th>6/4&quot;</th>
<th>8/4&quot;</th>
</tr>
</thead>
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<tr>
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<td>2.80</td>
<td>2.90</td>
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<td>3.09</td>
</tr>
</tbody>
</table>

Dried by T4-D2
Dried by T3-D1
From (4)
of 870,000 Btu/Mfbm between minimum and maximum for 8/4 lumber kiln-dried from 80 to 7 percent MC.

A broader picture of the effect of thickness on energy consumption is shown in Figure 4. Depending on initial MC, the total energy required to kiln-dry 4/4 lumber ranged from about 3 to 6.5 MMBtu/Mfbm, and for 8/4 lumber from about 4 to 9.5 MMBtu/Mfbm.

Thickness and Energy Costs

As energy costs increase they become a more important factor in total drying costs and are worth examining more closely from the standpoints of total energy costs and of the effect of thickness variation. The dependence of total energy costs on energy costs per MMBtu, thickness variation, and initial MC is shown for 4/4 oak in Figure 5. Current energy costs are quite variable and, depending on geographical location and source (coal, oil, natural gas, electricity, or wood residue), range from less than 1 dollar to over 10 dollars per MMBtu (11). As an example, if energy costs 2 dollars per MMBtu (a realistic figure for oil and natural gas (11)), the cost to kiln-dry minimum, target, and maximum thickness 4/4 lumber from 50 to 7 percent MC would be $8.76, $9.02, and $9.32 per thousand board feet respectively.

The percent increase in energy costs between target and maximum, and between minimum and maximum, is not as large as the increases in total drying costs, which would be expected because drying time influences other kiln-drying cost factors besides energy costs. These percent increases are shown in Figure 6, and range from about a 3 percent increase from target to maximum thickness to greater than 6 percent from minimum to maximum thickness.

Summary

The data in the analyses of the general effect of thickness, and thickness variation, on drying time,
costs, and energy consumption in kiln-drying red oak lumber are only estimates, but the model used is based on carefully taken drying-rate data. In an earlier paper (10) we showed that while the model does have some shortcomings and could be refined, it does give a reasonably good estimate of drying time. Therefore the estimates presented in this paper are at least accurate enough that the general picture presented of the effect of thickness on drying time, costs, and energy consumption are valid. The potential benefits from controlling thickness variation in sawing are quite clear and could offer significant savings in kiln-drying costs.

The practical effects of thickness variation on kiln-drying time are controlled by the selection and use of kiln samples. Certain boards are selected to represent the drying rate of the entire load and, because they are used to determine drying time, it is the thickness and thickness variation of these boards that is relevant. The generally accepted method of selecting kiln samples is to choose some that represent the slower drying material in the load (thicker, wetter, heavier, wider) and some that represent the faster drying material (6). Hardwood schedules are usually controlled on the half of the kiln samples that dry more slowly so that drying defects are minimized. Thus in most operations the thicker boards caused by thickness variation in sawing will enter the process control mechanism and affect drying time.

**Literature Cited**