SURFACE TEMPERATURE AS AN INDICATOR OF WOOD MOISTURE CONTENT DURING DRYING

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ABSTRACT

Average thickness, specific gravity, initial moisture content, elapsed time in oven, and surface temperature data were obtained for short sections of ponderosa pine board dried in a forced-air circulation oven. These data were subjected to a multiple regression analysis to determine their value as predictors of average wood moisture content. Results of the analysis showed that a model including surface temperature and elapsed time had an R^2 value of 0.89. From this, it appears that surface temperature and time could be used effectively for monitoring the moisture content of wood during drying. Infrared sensing devices promise easy measurement of surface temperature in such processes.

INTRODUCTION

The drying of wood from the green condition has been categorized into two drying periods, exclusive of the initial warmup interval. In the first period--the constant-rate period--the drying rate per unit of drying surface is constant. This is succeeded by a falling-rate period in which the water removal rate is gradually deceased. The wood moisture content at the point of change from a constant-rate to a falling-rate period has been termed the critical moisture content. During the constant-rate period, free water is evaporated. During the falling-rate period, bound water and water vapor are moved from the interior of the wood to the surface.

When the water evaporates from a wood surface, the heat of vaporization cools the surface. The cooling effect is relatively uniform during the constant-rate period but tends to decrease during the falling-rate period. Because of this predictable change in cooling, it has been hypothesized that a relation exists between the moisture content of a piece of wood and its surface temperature (fig. 1).

If wood surface temperature can be used as the control factor in the forced-air drying of individual pieces of lumber, prospects for the development of automatic, continuous drying processes will be enhanced.

The development of such a drying system is the objective of research being conducted by the Intermountain Forest and Range Experiment Station scientists stationed at the Forestry Sciences Laboratory in Missoula, Montana. Reported here are the results of one phase of this broad research effort--in which the strength of wood moisture prediction models was explored. Independent variables included: surface temperature, initial moisture content, specific gravity, wood thickness, and elapsed time.

PROCEDURE

Two select grade 1-inch by 6-inch by 18-foot rough green ponderosa pine boards were chosen at the green chain of a Missoula, Montana, sawmill. Both boards were flat-grained sapwood and were selected sufficiently far enough apart in the pile to insure that they had been cut from different logs.

The boards were cut into sections 3 inches long; any sections containing defects were discarded. All sections were identified as to board and maintained in a green condition until used by immersing them in water. At the time of testing, five sections from each board were removed from the tank, numbered consecutively, end-coated with an asphalt paint, and weighed. Seven replications were made using material from each board. Thus, a total of 70 sections was dried.

Test specimens obtained from the first board had a mean thickness of 0.941 inch, range 0.138 inch; mean specific gravity (green volume-ovendry weight) of 0.398, range 0.058; and mean initial moisture content of 161 percent, range 44 percent. For the second board the mean thickness of the test specimens was 0.964, range 0.095 inch; mean specific gravity (green volume-ovendry weight) 0.347, range 0.041; and mean initial moisture content 202 percent, range 52 percent.

A 4-mil copper-constantan thermocouple was inserted at the approximate center of the tangential face of each section as close to the surface as possible. The ideal procedure would have been to have the thermocouple half embedded and half exposed on the surface. But this was impossible; so a small cut, about 1/8-inch deep by 1/4-inch long, was made in each section surface using a scalpel, and the thermocouple was carefully inserted in the cut.

The sections were then placed on two wood strips alined crosswise in a forced-air circulation drying oven, which had been preheated to 180° F. The sections were thus positioned on edge at right angles to the airflow so that the air flowed over the specimen surfaces. The airspeed on the specimen surfaces was about 150 feet per minute.

The surface temperature of the sections and the oven temperature were recorded at 10-minute intervals during the drying period. As each section attained its assigned temperature it was removed from the oven and weighed. Sections were removed at surface temperatures of 120°, 130°, 140°, 150°, and 160° F.

After weighing, the sections were ovendried in a second oven in which the temperature was maintained at about 220° F. The initial as well as the percent moisture content at the time the sections were removed from the first oven were then calculated. End-coating had a negligible effect on the percent moisture content values.

The average thickness of each section then was determined by averaging three measurements made with a micrometer caliper.

A 1-inch cube was next cut from the approximate center of each test section and used for specific gravity determination. All cubes were impregnated with water to return them to a green condition so that volume could be determined by water immersion. The cubes were then ovendried and the specific gravity calculated.

Finally, the data for all sections--average thickness, specific gravity, initial moisture content, elapsed time in the oven, surface temperature, and the dependent variable (moisture content at time of removal from oven) were subjected to multiple regression analysis.

The algebraic form of the input variables was determined using two- and three-dimensional trends that appeared to be present in the data. Moisture content was expressed as a function of every combination of the independent variables and their transforms. The strength of each of these regression components then was evaluated on the basis of its contribution to R^2 in the full array of models thus assembled. Statistical tests of component contributions to R^2 were not attempted in this complete-screening analytical approach, but increases of 0.05 in R^2 were tentatively regarded as real. Expected and finally adopted forms for the moisture content (M) and the independent variables were as follows:

1. Moisture content (M) vs. elapsed time (E) and board thickness (T). --Expected relations are shown in figure 2 but neither a curvilinear main effect of T nor an interaction T-effect appeared to be present in the data--probably because of the very small range of T in the wood sections tested (range = 0.16 inch, with mean = 0.94 inch). As a result, T was admitted to analysis only as an independent linear effect. Values for E ranged up to 330 minutes. The E effect was well characterized by $(5-0.01E)^{1.5}$ and this form was used throughout the analysis.

2. M vs. E and specific gravity (G). --Expected relations are shown in figure 3 but, again, neither a curvilinear main effect of G nor the expected interaction was apparent in the data. The range of G was 0.11 with a mean of 0.37. So G also was admitted to analysis only as an independent linear effect.

3. M vs. E and initial moisture content (I). --An interaction of the two variables was readily apparent in the data. The I-effect was linear--which possibly can be attributed to the fairly narrow range of I encountered (range = 74 percent with a mean = 161 percent). The surface was well characterized by the form $(5 - 0.01E)^{1.5}$ (I). The expected relation between moisture content and elapsed time for three different initial moisture content levels is similar to that shown in figure 2.

4. M vs. E and surface temperature (S). --A curvilinear main effect of S appeared to be present in the data, but an interaction was not. S, maximum $\leq$ 180° F., was admitted to the analysis only as an independent linear effect. The expected relation between moisture content and elapsed time for three surface temperature levels is similar to that shown in figure 3.

RESULTS AND DISCUSSION

In combination with elapsed time, surface temperature and specific gravity proves to be strong contributors to the model in which moisture content was estimated.

The analysis showed that surface temperature alone was not a strong estimating base ($R^2 = 0.68$ for moisture content). For elapsed time alone, the R^2 was 0.84. An additive model combining surface temperature and elapsed time improved the R^2 to 0.89. By including surface temperature, elapsed time, and specific gravity in the model, the R^2 value was still further improved to 0.95. Only by adding initial moisture content could the strength of the estimating equation be further increased (table 1). The last model must be rejected, however, because it is impossible with the present state of technology to determine the initial moisture content before drying. Too, the model involving specific gravity must be discarded for the present, since specific gravity is difficult to measure.

The most practical model, then, includes only two variables--surface temperature and elapsed time. This model is shown in figure 4 and a few of the estimated values are shown in table 2.

Table 1. Independent variables and their combinations with corresponding R^2 values.

Variable	R^2
Surface temperature (S)	0.68
Elapsed time (E)	.84
S + E	.89
S + E + specific gravity (G)	.95
S + E + initial moisture content (I)	.96
E + I	.96

The strength of the relationship would probably have been weaker if the test material had not been so uniform. Ponderosa pine was the only species studied, but other softwood species could be expected to behave in a similar manner. Exploratory tests with Douglas-fir confirm this.

Surface temperatures, however, can be measured fairly easily. It is difficult to visualize thermocouples, as used in this study, being used in commercial drying. But it has been demonstrated that infrared sensing instruments are easy to use and are accurate for measuring surface temperatures. This greatly enhances the industrial potential of the surface temperature-elapsed time method of estimating moisture content.

A frequent but not always reproducible plateauing of surface temperature appeared to be associated with the

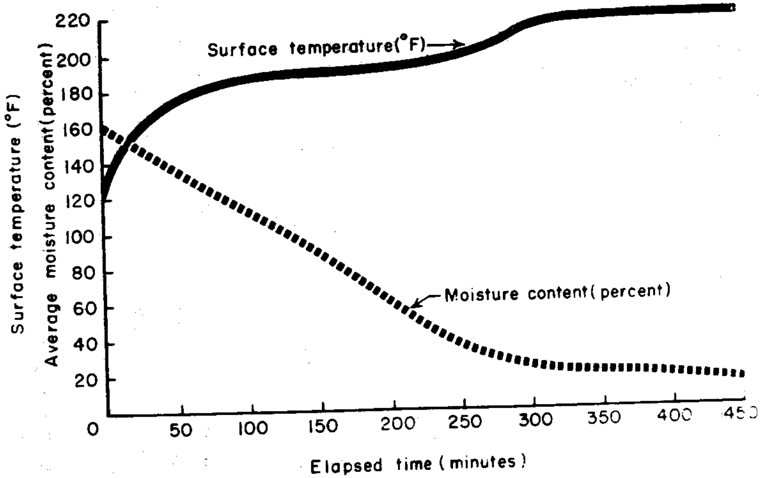

Figure 1. Typical graph from another study showing the relation between surface temperature-elapsed time and average percent moisture content-elapsed time. The flat-sawn ponderosa pine specimen, 19 inches long, was dried below the fiber saturation point at 230° F and 300 feet per minute airspeed.

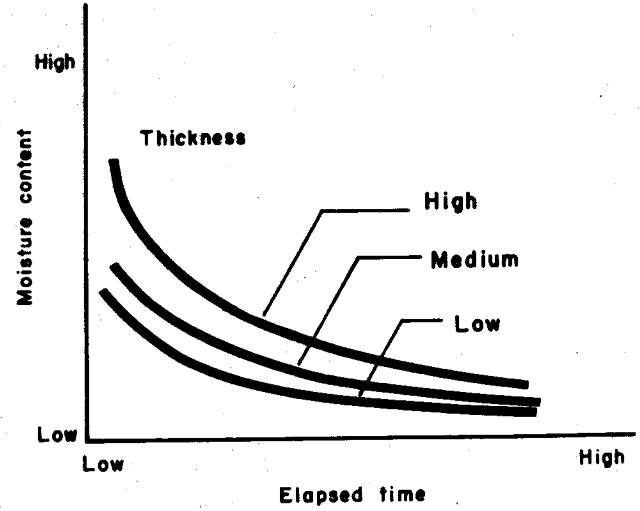

Figure 2. Expected relation between moisture content and elapsed time for three thicknesses.

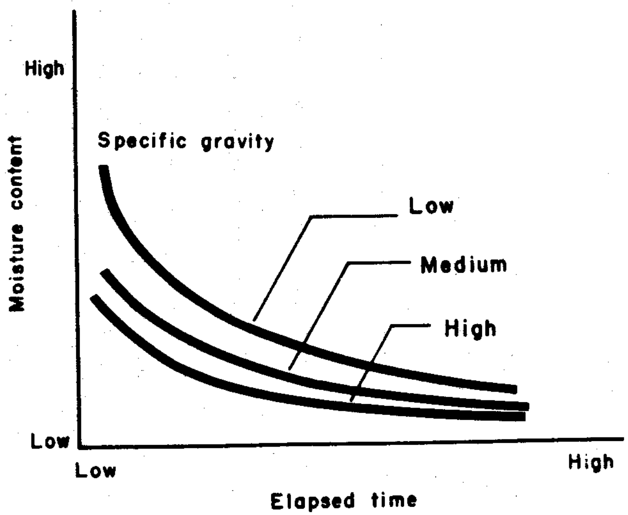

Figure 3. Expected relation between moisture content and elapsed time for three different levels of specific gravity.

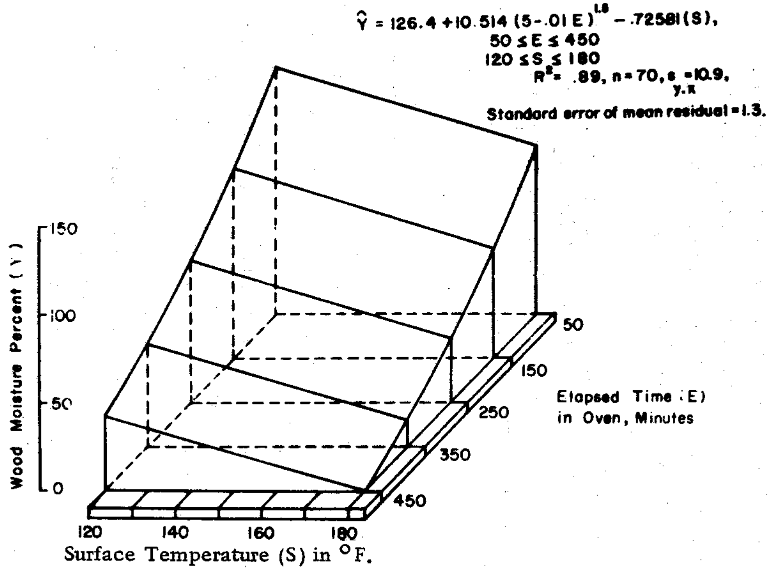

Figure 4. Three-dimensional model showing relation between surface temperature and elapsed time for a specific gravity level of 0.450.

constant rate period (Figure 1). Investigation of this characteristic may establish a technique for deciding when to shift drying conditions so that optimum conditions can be employed for both constant-rate and falling-rate drying periods.

Table 2. Predicted values for moisture content[1] based on elapsed time, surface temperature, and specific gravity.[2]

Surface temperature (°F)	Elapsed time (minutes)						
	50	100	150	200	250	300	350
				Percent			
120	120	101	84	68	53	40	28
130	114	96	79	63	48	35	23
140	109	91	74	57	43	29	18
150	103	86	68	52	37	24	12
160	99	80	63	47	32	19	7
170	93	75	58	42	27	14	1
180	88	70	52	36	22	8	0

[1] Drying temperature was 180° F and airspeed was 150 feet per minute.

[2] The specific gravity value used was 0.450.

CONCLUSIONS

A fairly reliable estimate of wood moisture content during drying can be made by using surface temperature and elapsed time. It is important to be able to measure initial moisture content and specific gravity easily--and there is need for further research on this problem. Although only ponderosa pine was used in this study, tentative tests with Douglas-fir indicated that the study results should have general application to other softwood species. A wood-drying monitoring system involving surface temperature appears promising.