HEAT FLUX AS A PREDICTOR OF MOISTURE CONTENT

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INTRODUCTION

The energy required to dry wood can be divided into two areas, 1) that actually used to remove water from wood, and 2) that which is lost as a result of venting and transmission losses through the kiln structure. Energy used to remove water from wood can be divided into the heat of vaporization, the heat of sorption, and the sensible heat associated with raising the temperature of the wood. Of these, energy used for evaporation (i.e., the heat of vaporization) is significantly larger than the other two energy requirements. The relationship between the energy used to remove water from wood and evaporation implies that energy flow into a sample can be used to predict moisture loss during drying. Since the sensible heat and the heat of sorption are small relative to the heat of vaporization, these energy requirements have a negligible effect on the relationship between moisture content and heat flow. Measuring heat flow into drying material is potentially a reliable nondestructive method for predicting moisture content and/or drying rate and therefore could provide the basis for a control system for drying wood products.

Heat flux sensors have been used by forest products researchers to measure transmission losses through the kiln structure (Arganbright et al. 1979; Laytner and Arganbright 1984). In these applications, the sensor was attached to the outside of a kiln wall while the kiln was operating, and the heat flow was measured for a short period of time. By making readings over a wide variety of locations a measure of within-kiln variability of heat loss was obtained. More recently Vanek (1989, 1990) conducted experiments using both embedded thermocouples and a heat flux sensor to predict or estimate moisture content during drying for the purpose of determining the drying rate and/or end-point. Vanek obtained good results using the heat flux sensor, and reported that the results were more reliable than those obtained using embedded thermocouples.

Some researchers have also investigated using internal temperature as an indication of average moisture content. Bai and Garrahan (1984) and Panow and Nester (1985) reported good results using this technique, whereas Holmes and Forrer (1989) reported that their results were not as promising.

A fundamental discussion of heat flux sensors, both with regard to application assumptions and design considerations was given by Scott (1976). The advantage of a heat flux sensor to obtain surface heat flux values over methods using a temperature measurement device (i.e., thermocouple, resistance temperature device (RTD), or thermistor) embedded in the wood sample is that assumptions regarding internal and external resistances are not as critical, and it is not necessary to know accurate values of material physical properties such as thermal conductivity, density, heat capacity and thickness.
The objective of this paper was to determine the relationship between heat flow into the wood during drying, measured using a heat flux sensor, and moisture content.

MATERIALS AND METHODS

Heat Flux Sensor

A model F-020-4 heat flux sensor manufactured by Concept Engineering, Inc., Old Saybrook, CT was used for all experiments. The sensor had a contact surface of 1.0 inch by 1.0 inch and was 0.10 inches thick. The calibration constant for the sensor was 21.0 BTU/hr*ft²/mV and the time constant was 14 s. A silicone heat sink compound (high thermal conductivity) was used to couple the heat flux sensor to the wood specimens. The sensor was held in place by two small leaf springs.

Specimen Material

Ponderosa pine (*Pinus ponderosa*) was used for all drying runs. The specimens were 6 inches by 9 inches. One- and two-inch thick material was tested. This material is referred to as 4/4 and 8/4, respectively, in the text. All specimens were edge sealed with silicon caulk and one layer of aluminum foil.

Experimental Procedure

Prior to each drying run the specimen was weighed in order to obtain an initial mass. The heat flux sensor was then attached, and the specimen was mounted on a 5-pound electronic load cell (Figure 1). A microcomputer-based data acquisition system was used to collect heat flux and load cell data at 6-minute intervals. These files were subsequently imported into a spreadsheet for analysis. Instantaneous heat flow and cumulative heat flow were analyzed as a function of drying time and moisture content.

After each drying run, the flux sensor was removed, the specimen was weighed to obtain an after drying mass, and then oven-dried and weighed again. Moisture content information generated from the initial, final and oven-dry masses were used to calculate moisture content data from the load cell readings.

Two drying schedules were used: 1) 180°F DBT/120°F WBT, and 2) 160°F DBT/120°F WBT. The dry-bulb temperature and wet-bulb temperature are abbreviated with DBT and WBT, respectively.

RESULTS AND DISCUSSION

The results presented here will be limited to four drying runs, one at each drying schedule and thickness combination. This is admittedly a small sample size, and consequently this report is intended to convey preliminary results only. Additional runs have been completed which confirm the results which will be discussed. Additional runs are planned, and their results will be published in a future paper.

Since the trends exhibited in the data were very similar between runs, discussion will concentrate on one 8/4 and one 4/4 run. The results of the 180/120°F 8/4 run are graphically presented in Figures 2 through 4. As shown in Figure 2, cumulative heat flow increased over the course of the run and eventually approached a constant value (i.e., the change in heat flow per unit time decreased) as the moisture content approached the kiln equilibrium moisture content condition. The trend observed in the cumulative heat flow curve agree with that expected from
Figure 1. Photograph of an 8/4 specimen mounted on the load cell platform. The heat flux sensor is mounted in the center of the specimen and is held in place using two small leaf springs.
Figure 2. Cumulative heat flow and moisture content as a function of drying time for the 8/4 sample dried at 180°F/120°F.

Figure 3. Instantaneous heat flow and moisture content as a function of drying time for the 8/4 sample dried at 180°F/120°F.
Figure 4. Moisture content as a function of cumulative heat flow for the 8/4 sample dried at 180°/120° F.

Figure 5. Cumulative heat flow and moisture content as a function of drying time for the 4/4 sample dried at 160° F/120° F.
Figure 6. Instantaneous heat flow and moisture content as a function of drying time for the 4/4 sample dried at 160° F/120° F.

Figure 7. Moisture content as a function of cumulative heat flow for the 4/4 sample dried at 160° F/120° F.
theoretical considerations. Heat flow to the wood is initially high, supplying both sensible and latent heat, to heat up the wood and evaporate moisture from it. As the drying rate decreases and the moisture content approaches an equilibrium value, heat flow into the specimen diminishes. Vanek (1989, 1990) did not utilize cumulative heat flow in his analysis.

Instantaneous heat flow measured at six-minute intervals and moisture content as a function of drying time is shown in Figure 3. The initial readings were beyond the range of the data acquisition system, as indicated by the constant reading. The trend exhibited in the instantaneous heat flow curve is similar to that observed in the moisture content curve, in that both decreased as a function of drying time. The heat flow approached zero as the moisture content approached the kiln equilibrium moisture content condition towards the end of drying. The trend exhibited in the instantaneous heat flow readings are similar to those reported by Vanek (1989, 1990), although he related heat flow to drying rate instead of moisture content (Vanek did not utilize cumulative heat flow in his analysis). The advantage of relating heat flow to moisture content instead of drying rate is that moisture content-based drying schedules have already been developed.

It is clear from Figure 3 that the instantaneous readings at six-minute intervals are more variable than the cumulative readings. The variability observed during the other runs was typically greater than that shown here. This variability could be reduced by taking more readings during the interval and then averaging. Subsequent experiments will incorporate such a procedure in the data acquisition software.

The relationship between moisture content and cumulative heat flow is shown in Figure 4. Although the initial portion of the curve is non-linear the remaining portion of the curve appears to be very linear. Linear regression conducted on the raw data yielded an overall coefficient of determination, $r^2$, of 0.99. This graph shows that measuring cumulative heat flow has good potential for use as a nondestructive method to predict moisture content from near the green to the oven-dry condition.

The $r^2$ values and regression equations generated from linear regression analysis of the moisture content and cumulative heat flow data from the four drying runs are given in Table 1. The $r^2$ values were consistently very good, always being greater than 0.95. These $r^2$ values show the potential usefulness of cumulative heat flow as a nondestructive method of predicting moisture content or drying rate. The ratio of the slopes from the 4/4 and 8/4 equations are between 1.5 and 2, indicating that, on a per percent moisture content basis, more energy is required to dry the 8/4 material. This is expected since there is a larger mass of water per percent moisture content in the 8/4 specimens. However, this does give additional evidence that cumulative heat flow is a valid nondestructive technique for measuring moisture content and/or drying rate. For example, for the two runs being discussed in detail in this paper, the ratio of the slopes (4/4:8/4) is 2.0 (0.22/0.11). The ratio of the mass of moisture lost per percent decrease in moisture content is also 2.0 (6.45g/3.15g). Therefore, the energy required per unit mass of moisture lost, as measured with the heat flux sensor, would be the same regardless of thickness.

Curves for 4/4 material, dried at 160°/120° F, are shown in Figures 5 through 7. The relationships observed here are very similar to those observed for the 8/4 material. As shown in Figure 5, the sample was at the kiln equilibrium moisture content condition during the last 10 hours of the run, and the cumulative heat flow remained unchanged over the same interval. The agreement between
Table 1. The coefficient of determination, $r^2$, and regression equation resulting from linear regression analysis using test data. The regression equations are given in terms of moisture content (MC) and cumulative heat flow (CumHeat).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Schedule</th>
<th>$r^2$</th>
<th>Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/4</td>
<td>180/120</td>
<td>0.99</td>
<td>$MC = -0.11(CumHeat) + 175.0$</td>
</tr>
<tr>
<td>8/4</td>
<td>160/120</td>
<td>0.99</td>
<td>$MC = -0.16(CumHeat) + 182.5$</td>
</tr>
<tr>
<td>4/4</td>
<td>180/120</td>
<td>0.97</td>
<td>$MC = -0.21(CumHeat) + 166.3$</td>
</tr>
<tr>
<td>4/4</td>
<td>160/120</td>
<td>0.97</td>
<td>$MC = -0.22(CumHeat) + 165.1$</td>
</tr>
</tbody>
</table>

cumulative heat flow and moisture content at low moisture contents is another indication that the heat flow readings are reliable. As shown in Figure 6, the instantaneous heat flow readings are again quite variable. The readings shown here are much more variable than those observed with the 8/4 specimen (Figure 3). Note that the initial energy transfer to the wood specimen did not exceed the range of the data acquisition system, probably because of the lower DBT. The initial moisture contents of the 8/4 and 4/4 samples were similar. The instantaneous heat flow was essentially zero during the period when no drying was occurring. The relationship between moisture content and cumulative heat flow is again quite good, with an $r^2$ of 0.97 (the raw data are plotted in Figure 7). In this case, the moisture content range over which prediction would be possible is again from near the green to the oven-dry condition.

**SUMMARY AND CONCLUSION**

It is evident from these preliminary data that cumulative heat flow is potentially a very good predictor of moisture content over most of the moisture content range from near green to oven-dry. The instantaneous heat flow value was quite variable, and the amount of variability would likely increase with the increased temperature variability that may be expected in a commercial kiln. The variability in the 6-minute interval instantaneous values could be reduced by taking several readings over the interval and averaging. This technique will be used in subsequent tests. In addition, subsequent tests will compare the theoretical amount of energy required for drying to the amount actually utilized based on the heat flux sensor measurements.
REFERENCES


