WOOD PRODUCTS NOTES

Department of Forest Biomaterials Campus Box 8003 North Carolina State University Raleigh, North Carolina 27695-8003

Summary: If given enough time the moisture content of wood will come to an equilibrium with the surrounding environment. The temperature and relative humidity of the surrounding air will establish equilibrium moisture content (EMC) conditions, and the moisture content of the wood in that environment will approach the EMC of the air.

This issue of Wood Products Notes introduces the "EMC Calculate" Excel spreadsheet that will calculate an estimate of the EMC based on one of the following pairs of data:

- Relative humidity and dry-bulb temperature;
- Wet-bulb temperature and dry-bulb temperature; or
- Dew-point temperature and dry-bulb temperature.

Phil Mitchell
Wood Products Extension
Campus Box 8003
Raleigh, NC 27695
(919) 515-5581 Phone
phil_mitchell@ncsu.edu
https://research.cnr.ncsu.edu/blogs/wpe/

Calculating the Equilibrium Moisture Content for Wood Based on Humidity Measurements

By Phil Mitchell
North Carolina State University

CONNECTING WOOD MOISTURE CONTENT TO RELATIVE HUMIDITY

The connection between the percent relative humidity and the corresponding wood moisture content has existed (at least) since an early Forest Products Lab publication (1919). Koehler and Thelen (1926) state "There is a definite relation between the moisture content of wood and the relative humidity of the atmosphere at any given temperature." One of the earliest uses of the term "equilibrium moisture content" was by Jenkins (1934). The moisture content of wood will, if given enough time, come to an equilibrium with the surrounding environment. The temperature and relative humidity of the surrounding air will establish equilibrium moisture content (EMC) conditions, and the moisture content of wood in that environment will approach the EMC of the air.

Although the relationship between relative humidity and EMC is not linear, there are some simple methods to relate the two. One method to get a very rough estimate of EMC is to divide the percent relative humidity by 5 (McConnell, 2016). Thus for a relative humidity of 75%, the estimated EMC would be 15%. A better estimate is provided by Table 1 which presents selected points along the EMC versus RH curve. For the given relative humidity, EMC is approximately $\pm$1 percent EMC of the stated value at temperatures between 35°F to 100°F (Wengert, 1988).

Table 1. Approximate relationship between %RH and %EMC valid to $\pm$ 1% EMC from 35°F to 100°F.

% RH	% EMC
20	4
30	6
50	9
66	12
75	14
80	16

NC State University A&T State University COOPERATIVE EXTENSION Empowering People · Providing Solutions

The most extensive and published authoritative source for EMC derived from dry-bulb / wet-bulb temperatures is the USDA's Dry Kiln Operator's Manual, first published in 1960 and updated in 1991 (Forest Products Laboratory 1960, 1991). The EMC – RH relationship compiled in Table 1-6 of that publication has been used to construct and adjust lumber dry kiln schedules and serves as the basis of comparison for this work.

A Single Software Tool to Calculate the EMC

There are programs available on the web to calculate EMC based on relative humidity and dry-bulb temperature, or to calculate relative humidity by combining dry-bulb temperature with either wet-bulb temperature or dew-point temperature. The Wood.xls program was released by Oregon State University which can calculate EMC based on relative humidity and temperature (Leavengood, 2001). Similarly, the Equilibrium Moisture Content Calculator can do the same (Penn State Extension, 2016). In addition, although it does not calculate the EMC, the National Oceanic and Atmospheric Administration presents a web page that calculates the wet-bulb and dew-point temperatures based on temperature and relative humidity (NOAA, 2016).

What is missing is a single tool that can quickly provide an estimate of EMC based on any of the more commonly used humidity measurements typically employed in manufacturing wood products or in the evaluation of product performance. These humidity measurements include:

- Direct measurement of relative humidity;
- Determination of wet-bulb temperature such as often found in lumber dry kilns;
- Determination of dew-point temperature such as found in equilibrium moisture content chambers and commonly used in local weather forecasts.

This issue of Wood Products Notes introduces an Excel spreadsheet that will serve as a single tool capable of estimating EMC using the available humidity measurement. The "EMC Calculate" spreadsheet will calculate an estimate of the EMC based on only two pieces of data that the user provides. The user may select one of the following to determine EMC:

- Dry-bulb temperature and relative humidity;
- Dry-bulb temperature and wet-bulb temperature;
- Dry-bulb temperature and dew-point temperature.

This will prove useful to the dry kiln operator that might have dry-bulb and wet-bulb measurements from the dry kiln or relative humidity measurements from an electronic sensor in the predryer, or to the plant engineer using a sling psychrometer to measure the RH on the factory floor or in a warehouse, or to the consultant trying to determine the immediate EMC of an environment that contains wood products and perhaps the impact of recent relative humidity trends, or to a lumber yard manager interested in the impact of current or average monthly weather conditions on his air drying lumber.

The Excel spreadsheet can be obtained by emailing the author, or downloading it from the North Carolina State University Wood Products Extension website.

The remainder of this article provides details on how the spreadsheet calculates EMC from relative humidity, and how it calculates relative humidity from dry-bulb temperatures and either wet-bulb or dew-point temperatures.

CALCULATING THE EMC FROM THE RELATIVE HUMIDITY

Although the relationship between relative humidity and equilibrium moisture content is not linear, an increase in relative humidity or a decrease in dry-bulb temperature will increase the EMC of the air. The non-linear nature of the RH-EMC relationship is a typical sorption isotherm and has been described by sorption theory. An adsorption model employed by Simpson (1973) uses the theory developed by Hailwood and Horrobin (1946) to predict the EMC based on the combination of temperature and relative humidity. The form of the equation is:

$$EMC = \frac{1800}{W}\left(\frac{Kh}{1-Kh} + \frac{(K_1Kh + 2K_1K_2K^2h^2)}{(1 + K_1Kh + K_1K_2K^2h^2)}\right) \qquad \text{Eq. 1}$$

where:

EMC is the equilibrium moisture content (%)
h is relative humidity expressed in decimal form (% / 100)
W, K, K_1 and K_2 are coefficients.

These coefficients are defined by the following equations where T is the dry-bulb temperature in degrees Fahrenheit:

$$W = 330 + 0.452T + 0.00415T^2 \qquad \text{Eq. 2}$$
$$K = 0.791 + 0.000463T - 0.000000844T^2 \qquad \text{Eq. 3}$$
$$K_1 = 6.34 + 0.000775T - 0.0000935T^2 \qquad \text{Eq. 4}$$
$$K_2 = 1.09 + 0.0284T - 0.0000904T^2 \qquad \text{Eq. 5}$$

Thus, given two pieces of information, dry-bulb (ambient) temperature and the relative humidity, the EMC that those conditions establish can be readily calculated.

Relative humidity may be measured directly with certain instruments. If we are given RH and temperature then the Hailwood-Horrobin equation listed above can be used directly to calculate EMC. However, some instruments measure humidity in terms of dew-point temperature or wet-bulb temperature. The following sections describe the use of these various humidity measurements to estimate EMC.

CALCULATING RELATIVE HUMIDITY FROM WET-BULB TEMPERATURE

Wet-bulb thermometers are a simple, relatively inexpensive means to measure the humidity in an environment. Their ruggedness and simplicity make them useful in the lumber dry kiln environment. Today kiln operators might use the tables found in the Dry Kiln Operator’s Manual to determine RH and EMC from dry-bulb and wet-bulb temperatures, or their computer control system may make the conversion automatically.

The determination of the percent relative humidity based on wet-bulb temperature can be approximated by the following equation (Smithsonian Meteorological Tables, 1951):

$$\%\,RH = 100 \times \left(\frac{p_w - 0.000660\,P\,(T_d - T_w)\,(1 + 0.00115\,T_w)}{p_o}\right) \qquad \text{Eq. 6}$$

where:

T_d is the dry-bulb temperature, °C
T_w is the wet-bulb temperature, °C
P is the atmospheric pressure, (usually 760 mm Hg)
p_o is the saturated vapor pressure at the dry-bulb temperature, mm Hg
p_w is the vapor pressure at the wet-bulb temperature, mm Hg

The vapor pressures p_o and p_w can be approximated using the following equations from Skaar (1978):

$$p_w = 10^{7.96427} \times 10^{(-1628.445 / (Tw + 273.1))} \times 10^{(-100151 / (Tw + 273.1)^2)} \quad \text{Eq. 7}$$

$$p_o = 10^{7.96427} \times 10^{(-1628.445 / (Td + 273.1))} \times 10^{(-100151 / (Td + 273.1)^2)} \quad \text{Eq. 8}$$

As indicated, when used these equations provide an approximation of the relative humidity. For most practical applications that approximation is adequate.

Once the RH has been calculated from the dry-bulb and wet-bulb temperatures, the EMC can be calculated using the Hailwood-Horribin sorption model (Equations 1 through 5).

Calculating Relative Humidity from Dew-point Temperature

Dew-point measurement has been considered to be a more accurate method for determining relative humidity compared to wet-bulb temperature measurement. However, for many industrial applications the technology is less rugged and too expensive compared to the use of a wet-bulb. Dew-point temperatures are typically measured and reported by local weather stations, and can be used to determine both relative humidity and EMC.

The equation used to calculate relative humidity from dew-point and dry-bulb temperatures is related to and derived from the vapor pressure equations (Eq. 7 & 8) above, and their empirical nature is pointed out (Skaar, 1972).

$$\% RH = 100 \times \left(10^{\{1628.445 * [(1/(T_d+273.15)) - (1/(T_{dp}+273.15))]\}} \times 10^{\{100151 * [(1/(T_d+273.15)^2) - (1/(T_{dp}+273.15)^2)]\}}\right) \quad \text{Eq. 9}$$

where the new variable introduced is :

T_{dp} is the dew-point temperature, °C

The calculated percent relative humidity and corresponding dry-bulb temperature are then used to calculate the estimated EMC using the Hailwood-Horrobin sorption model (Equations 1 through 5).

Errors and Sources of Variation

The "EMC Calculate" program begins with either a known relative humidity to calculate EMC, or it calculates relative humidity at a specified dry-bulb temperature using either wet-bulb or dew-point temperature, and then it uses that information to calculate the EMC.

Generally, there is good agreement between the calculated EMC from the "EMC Calculate" spreadsheet and the tables published in the Dry Kiln Operator's Manual (1991). Over the range of dry-bulb temperatures from 35ºF – 180ºF and relative humidities ranging from approximately 20% to 80%, the calculated EMC differed from the tabulated EMC by no more than 0.5% EMC, and in the majority of instances differed no more than 0.2% EMC. The larger errors occurred at the higher dry-bulb temperatures (160ºF – 180ºF). As pointed out in the Dry Kiln Operator’s Manual (page 40), Equations 1 through 5 are least square regression fits of data and hence “they give estimates close to but not exactly the same as those in the tables.”

The calculation of relative humidity from either wet-bulb temperature (Eq. 6) or dew-point temperature (Eq. 9) by the “EMC Calculate” spreadsheet agreed well with that given by the “Relative Humidity web page published by NOAA, with differences generally less than 0.5% relative humidity.

December 2017

Literature Cited

Forest Products Laboratory. 1919. “Correct moisture content of lumber.” Technical Note D5.

Forest Products Laboratory. 1991. *Dry Kiln Operator’s Manual*. Agricultural Handbook 188. Madison, WI. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 274 p.

Hailwood, A.J., Horrobin, S. 1946. “Absorption of water by polymers: analysis in terms of a simple model.” Transactions of Faraday Society. 42B: 84-92, 94-102.

Jenkins, J. H. 1934. *Kiln-Drying British Columbia Lumber*. Ottawa: Forest Products Laboratories of Canada. 78 p.

Koehler, A., & Thelen, R. 1926. *The Kiln Drying of Lumber*. New York, NY: McGraw-Hill Book Company, Inc. 293 p.

Leavengood, Scott. 2001. “Excel spreadsheet calculates dimensional change.” Forest Products Journal, 51 (11/12), 12.

McConnell, E. 2016. “Wood moisture relations and the shrinkage of wood,” Presentation at the Dry Kiln Operator’s Short Course, North Carolina State University, Raleigh, NC.

NOAA. 2016. National Weather Service Forecast Office “Relative Humidity” web page by Tim Brice and Todd Hall. http://www.srh.noaa.gov/epz/?n=wxcalc_rh accessed 9/22/2016.

Penn State Extension. 2016. Equilibrium Moisture Content Calculator. Accessed on 9/22/2016. http://extension.psu.edu/natural-resources/forests/woodpro/equilibrium-moisture-content-calculator .

Simpson, W.T. 1973. Predicting equilibrium moisture content of wood by mathematical models. Wood and Fiber. 5(1): 41-49.

Skaar, Christen. 1972. *Water in Wood*. Syracuse, NY. 218 p.

Skaar, Christen. 1978. Wood Physics class notes. Virginia Polytechnic University and State University. Communicated January 4, 1978. Blacksburg, VA.

Smithsonian Meteorological Tables. 1951. 6th Edition, Robert J. List, ed., Smithsonian Institution, Washington, DC.

Wengert, G. 1988. Relationship of Humidity, Wood Moisture, and Shrinkage. In *The Wood Doctor’s Rx* (pp. 339–346). Blacksburg: Virginia Polytechnic Institute and State University.