Calculating the Equilibrium Moisture Content for Wood Based on Humidity Measurements

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If given enough time, the moisture content of wood will reach an equilibrium with its surrounding environment. The temperature and relative humidity (RH) of the surrounding air will establish equilibrium moisture content (EMC) conditions, and the moisture content of the wood in that environment will approach a value determined by the RH. This article introduces an Excel spreadsheet that will calculate an estimate of the EMC based on any one of the following three pairs of data: RH and dry-bulb temperature, wet-bulb temperature and dry-bulb temperature, or dew-point temperature and dry-bulb temperature.

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INTRODUCTION

The connection between relative humidity (% RH) and the corresponding wood moisture content has existed (at least) since an early Forest Products Laboratory 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 its surrounding environment. The temperature and RH of the surrounding air will establish equilibrium moisture content (EMC) conditions and the moisture content of wood in that environment will approach the EMC conditions of the air, although species and previous moisture history have a slight effect (Simpson 1991).

Although the relationship between RH and EMC is not linear, there are some simple methods to relate the two. One approach to estimate the EMC is to divide the percent RH by a factor of 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* the RH curve.

Table 1. Approximate Relationship between %RH and %EMC Valid to ± 1% EMC from 35 °F to 100 °F

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

For a given relative humidity, the EMC is approximately ± 1% EMC of the stated value at temperatures between 35 °F to 100 °F (Wengert 1988).

The most extensive and published authoritative source for EMC derived from dry-bulb and 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 Tables 1 through 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.

There are programs available on the web to calculate the EMC based on RH and dry-bulb temperature, or to calculate RH by combining dry-bulb temperature with either wet-bulb temperature or dew-point temperature. The Wood.xls program released by Oregon State University 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 (NOAA) presents a psychrometric calculator on a web page that calculates the wet-bulb and dew-point temperatures based on temperature and relative humidity (Brice and Hall 2016).

What is missing is a single tool that can quickly provide an estimate of EMC based on any of the humidity measurements typically used for manufacturing wood products or in the evaluation of product performance. These humidity measurements include the direct measurement of RH, determination of wet-bulb temperature, such as often found in lumber dry kilns, and determination of dew-point temperature such as found in equilibrium moisture content chambers and commonly used in local weather forecasts.

This article introduces an Excel spreadsheet that will serve as a single tool capable of estimating wood 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 the EMC: dry-bulb temperature and RH, dry-bulb temperature and wet-bulb temperature, or 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 RH measurements from an electronic sensor in the predryer), to the plant engineer (using a sling psychrometer to measure the RH on the factory floor or in a warehouse), 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 the lumber yard manager (interested in the impact of current or average monthly weather conditions on his air drying lumber).

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

EXPERIMENTAL

Calculating the EMC from the Relative Humidity

Although the relationship between RH and moisture content is not linear, an increase in RH or a decrease in temperature will increase the predicted moisture content of wood, after its equilibration with the air (EMC). 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 RH. The form of the equation is as seen in Eq. 1,

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

where *EMC* is the equilibrium moisture content (%), *h* is the relative humidity expressed in decimal form (% / 100), and *W*, *K*, K_1, and K_2 are coefficients defined by Eqs. 2 through 5, respectively,

$$W = 330 + 0.452T + 0.00415T^2 \quad (2)$$

$$K = 0.791 + 0.000463T - 0.000000844T^2 \quad (3)$$

$$K_1 = 6.34 + 0.000775T - 0.0000935T^2 \quad (4)$$

$$K_2 = 1.09 + 0.0284T - 0.0000904T^2 \quad (5)$$

where *T* is the dry-bulb temperature (°F).

Thus, given two pieces of information, dry-bulb (or ambient) temperature and the RH, the EMC can be readily calculated.

Relative humidity may be measured directly with certain instruments. If the RH and temperature are given, then the Hailwood-Horrobin sorption equation (Eq. 1) can be used to directly calculate the EMC. However, some instruments measure humidity in terms of dew-point temperature or wet-bulb temperature. The following sections describe their use.

Methods

Calculating relative humidity from wet-bulb temperature

Wet-bulb thermometers are a simple, relatively inexpensive way 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 (1991) to determine RH and EMC from dry-bulb and wet-bulb temperatures, or their computer control system may convert automatically.

The determination of the percent relative humidity based on wet-bulb temperature can be approximated by Eq. 6 (List 1951),

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

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), and 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 Eqs. 7 and 8 from Skaar (1978),

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

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

As indicated, these equations provide an approximation of the relative humidity. For most practical applications, this 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-Horrobin sorption model (Eqs. 1 through 5).

Calculating relative humidity from dew-point temperature

Dew-point measurement has been considered to be a more accurate method for determining RH compared to wet-bulb temperature measurement. However, for many industrial applications, the technology is less rugged and too expensive compared to that for wet-bulb temperature measurement. Dew-point values 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 (Eqs. 7 and 8) above, and their empirical nature is described (Skaar 1972),

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

where the new variable introduced, T_{dp}, is the dew-point temperature (°C).

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

RESULTS AND DISCUSSION

An Excel spreadsheet has been developed that is capable of estimating wood EMC using the available humidity measurements. The "EMC Calculate" spreadsheet calculated an estimate of the EMC based on only two pieces of data that the user provided. The user entered one of the following pairs of data to determine the EMC: dry-bulb temperature and relative humidity, dry-bulb temperature and wet-bulb temperature, or dry-bulb temperature and dew-point temperature.

Errors and Sources of Variation

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

Generally, there was 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 35 °F to 180 °F and RHs that ranged 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 higher dry-bulb temperatures (160 °F to 180 °F). As pointed out in the Dry Kiln Operator's Manual (1991), Eqs. 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 RH 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.

The Excel spreadsheet can be obtained by emailing the author, or downloading it from the North Carolina State University Wood Products Extension website (https://research.cnr.ncsu.edu/blogs/wpe/publications/).

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