EVALUATING HUMIDITY AT DRY BULB TEMPERATURES ABOVE THE NORMAL BOILING POINT OF WATER A RESEARCH NOTE

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ABSTRACT

Several methods were compared for evaluating relative humidities at temperatures between 210 and 300 F from psychrometric relations. An explicit method of calculating relative humidity, assuming that the wet bulb temperature is equivalent to the adiabatic saturation temperature, is shown to predict relative humidities with a maximum deviation of only 1% from those values predicted by more theoretically rigorous equations.

Keywords: Wet bulb temperature, dry bulb temperature, relative humidity, adiabatic saturation temperature.

NOTATION

A	area of wetted surface, ft^2
c	heat capacity, Btu/lb °F
D_v	diffusion coefficient, ft^2/h
h	heat transfer coefficient, Btu/hr ft^2 °F
ΔH_v	latent heat of vaporization, Btu/lb
k	thermal conductivity, Btu/ft °F h
N_{Le}	Lewis number, $k/c\rho D_v$
p	partial pressure of water vapor, psi
p^*	saturated pressure of water vapor, or above 212 F, vapor pressure of water, psi
p_t	total pressure of drying atmosphere, psi
RH	relative humidity, percent
T	temperature, °F
W	mass rate of evaporation, lb/h
x	film thickness, ft
Y	absolute humidity lb water vapor/lb dry air
β	constant, dimensionless
ρ	density, lb/ft^3

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Subscripts

a	air
db	dry bulb
f	air film
m	air-water vapor mixture
s	at adiabatic saturation temperature
wb	at wet bulb temperature
wv	water vapor

An adequate method for determining the humidity when kiln drying lumber at temperatures above 212 F is important. The physical quality of the dry lumber, the rate at which the lumber dries, and the final moisture content of the wood can all be controlled by regulating the humidity in the kiln. In nearly all lumber drying kilns, humidity is indirectly determined from a direct measurement of dry bulb and wet bulb temperature.

Equations developed from psychrometric theory, relating dry bulb and wet bulb temperature to relative humidity, are generally based on several simplified approximations derived from the theory. Applying these approximations, Zimmerman and Lavine (1964) have shown that at temperatures below 200 F and at low absolute humidity, the wet bulb temperature and adiabatic saturation temperature are equal. Most humidity charts and tables are presented in terms of adiabatic saturation temperatures or, if the wet bulb temperature is given, it has been assumed equal to the adiabatic saturation temperature.

We wanted to determine if the wet bulb temperature can be adequately represented by the adiabatic saturation temperature at conditions of practical importance when high-temperature drying lumber—210 to 300 F dry bulb temperature and 150 to 210 F wet bulb temperature. (Above 300 F the maximum equilibrium moisture content of wood is below 2.0%, and differences in humidity have little effect on changes in wood drying.) Relative humidity, calculated from wet bulb temperatures by two different approaches, was compared to that calculated from adiabatic saturation temperature.

RELATIVE HUMIDITY CALCULATED FROM ADIABATIC SATURATION TEMPERATURE

When an air and water vapor mixture is brought in contact with water, the air is cooled and humidified. The adiabatic saturation temperature, T_s, is reached when the temperature of the saturated air is the same as the water and no heat is lost to or gained from the surroundings. From an energy balance the equation relating absolute humidity, Y, to dry bulb temperature, T_{db}, and T_s is (Hawkins 1978):

$$Y = Y_s - \frac{(0.24 + 0.44Y_s)(T_{db} - T_s)}{1094 + 0.44T_{db} - T_s} \tag{1}$$

where

$$Y_s = \frac{p_s}{1.61(p_t - p_s)}. \tag{2}$$

The analysis by Hawkins (1978), similar to many standard approaches in the literature, is meant to cover a wide range of operating temperatures and thus assumes average values of 0.24 and 0.44 Btu/lb F for the heat capacity of air, c_a, and water vapor, c_{wv}, respectively. The value 1094 is the heat of vaporization of water at 0 F.

Humidities are reported in terms of relative humidity, RH, which is the percent of partial pressure of the water vapor at a given condition to that saturated partial pressure at the same temperature (Hawkins 1978):

$$p = \frac{1.61Yp_t}{1 + 1.61Y} \tag{3}$$

and

$$RH = \frac{p \times 100}{p^*}. \tag{4}$$

RELATIVE HUMIDITIES CALCULATED FROM WET BULB TEMPERATURES

When partially saturated air is passed over a wetted thermometer bulb, the water evaporates from the wetted surface causing the thermometer to cool. The wet bulb temperature, T_{wb}, is that equilibrium temperature at which the rate of heat transferred from the air by convection and conduction is equal to the rate the wetted surface loses heat in the form of latent heat of evaporation.

Approach by Rosen (1980)

By setting the sensible heat gained by the air equal to the heat lost by evaporation, the following equation is obtained:

$$h_fA(T_{db} - T_{wb}) = (\Delta H_v)_{wb}\, W. \tag{5}$$

After redefining terms and using several approximations (Rosen 1980), humidity can be related to dry bulb and wet bulb temperature by

$$Y = Y_{wb} - \frac{(N_{Le})^{2/3}c_m}{(\Delta H_v)_{wb}}(T_{db} - T_{wb}) \tag{6}$$

where

$$N_{Le} = \frac{k}{c_m \rho D_v} \tag{7}$$

$$c_m = c_a + Yc_{wv} \tag{8}$$

$$Y = \frac{p_{wb}}{1.61(p_t - p_{wb})}. \tag{9}$$

Partial pressure and relative humidity can be calculated from Eqs. 3 and 4, respectively.

Approach by Marshall (1978)

Marshall (1978) takes into account the sensible heat transferred to the molecules diffusing through the surface of the wet bulb wick as well as heat of evaporation

TABLE 1. *Comparison of relative humidity values as a function of wet and dry bulb temperatures by (a) approximation to adiabatic saturation temperature, (b) calculation technique of Rosen (1980)—in italics, and (c) calculation technique of Marshall (1978)—underlined.*

Dry bulb temperature, F	Wet bulb temperature, F								
	150	160	170	180	190	195	200	205	210
	24.5	32.1	41.4	52.5	65.8	73.3	81.5	90.4	100.0
210	*24.5*	*32.0*	*41.1*	*52.1*	*65.4*	*72.9*	*81.2*	*90.2*	*100.0*
	23.5	31.1	40.4	51.6	65.0	72.7	81.1	90.2	100.0
	22.0	28.9	37.3	47.3	59.4	66.1	73.5	81.6	90.3
215	*22.0*	*28.8*	*37.1*	*47.0*	*59.0*	*65.9*	*73.3*	*81.5*	*90.4*
	21.1	27.9	36.3	46.4	58.6	65.6	73.2	81.4	90.3
	19.9	26.2	33.9	43.1	54.0	60.2	67.0	74.3	82.3
220	*19.8*	*26.0*	*33.5*	*42.6*	*53.5*	*59.7*	*66.5*	*73.9*	*82.0*
	18.9	25.2	32.8	42.0	53.1	59.4	66.3	73.8	82.0
	17.9	23.6	30.7	39.0	49.0	54.7	60.8	67.5	74.7
225	*18.0*	*23.6*	*30.5*	*38.7*	*48.7*	*54.3*	*60.5*	*67.3*	*74.6*
	17.1	22.8	29.7	38.1	48.2	54.0	60.3	67.1	74.6
	16.2	21.5	27.8	35.4	44.5	49.7	55.3	61.3	67.9
230	*16.3*	*21.5*	*27.7*	*35.3*	*44.3*	*49.5*	*55.2*	*61.3*	*68.0*
	15.4	20.6	27.0	34.6	43.9	49.1	54.9	61.2	68.0
	14.7	19.4	25.2	32.2	40.5	45.2	50.3	55.9	61.9
235	*14.8*	*19.5*	*25.2*	*32.1*	*40.4*	*45.2*	*50.3*	*56.0*	*62.1*
	14.0	18.7	24.5	31.5	39.9	44.8	50.1	55.8	62.1
	13.3	17.7	23.0	29.3	36.9	41.2	45.9	51.0	56.5
240	*13.5*	*17.8*	*23.0*	*29.3*	*36.9*	*41.3*	*46.0*	*51.2*	*56.8*
	12.7	17.0	22.3	28.7	36.4	40.9	45.7	51.0	56.7
	11.0	14.7	19.1	24.5	30.9	34.5	38.4	42.7	47.3
250	*11.2*	*14.8*	*19.2*	*24.5*	*30.9*	*34.6*	*38.6*	*42.9*	*47.6*
	10.4	14.1	18.5	23.9	30.4	34.2	38.2	42.7	47.6
	9.2	12.3	16.0	20.6	26.0	29.0	32.4	36.0	39.9
260	*9.3*	*12.4*	*16.1*	*20.6*	*26.0*	*29.1*	*32.5*	*36.1*	*40.1*
	8.6	11.7	15.5	20.0	25.5	28.7	32.2	35.9	40.1
	7.0	9.4	12.4	15.9	20.1	22.6	25.2	28.0	31.1
275	*7.1*	*9.6*	*12.5*	*16.0*	*20.3*	*22.7*	*25.3*	*28.2*	*31.3*
	6.6	9.0	11.9	15.5	19.8	22.3	25.0	28.0	31.3
	4.6	6.2	8.3	10.7	13.6	15.2	17.0	18.9	21.0
300	*4.7*	*6.3*	*8.3*	*10.7*	*13.6*	*15.3*	*17.1*	*19.1*	*21.2*
	4.2	5.9	7.9	10.3	13.2	14.9	16.8	18.9	21.1

and sensible heat gained by the air. Thus, the heat balance is in a slightly different form than Rosen's:

$$k_f A\ dT/dx = W(\Delta H_v)_{wb} + Wc_{wv}(T_{db} - T_{wb}). \tag{10}$$

Solving this differential equation, redefining terms, and approximating the solution with a series solution

$$p = p_t - \left[(T_{db} - T_{wb})\frac{c_{wv}}{(\Delta H_v)_{wb}} + 1\right]^{1/\beta}(p_t - p_{wb}) \tag{11}$$

where

$$\beta = 0.622\frac{c_{wv}}{c_a}(N_{Le})^{2/3}. \tag{12}$$

Relative humidity can be calculated from Eq. 4.

COMPARISON OF METHODS FOR CALCULATING RELATIVE HUMIDITY

Calculation of relative humidities over a range of conditions based on (a) adiabatic saturation temperature, (b) the analysis by Rosen (1980), and (c) the analysis by Marshall (1978) are shown in Table 1. The maximum absolute deviation of relative humidity calculated by (b) and (c) from (a) is only 1.0% relative humidity. Average deviation between (a) and (b) is 0.2% and between (a) and (c) is 0.5%. The maximum deviation of relative humidity is less than the accuracy or precision required when drying lumber. Thus, wet bulb temperature is adequately represented by the adiabatic saturation temperature for conditions of dry bulb temperature from 210 to 300 F and wet bulb temperature from 150 to 210 F.

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