

PSYCHROMETRIC RELATIONSHIPS AND EQUILIBRIUM MOISTURE CONTENT OF WOOD AT TEMPERATURES ABOVE 212 F¹

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ABSTRACT

Equations are derived to evaluate psychrometric relationships over a range of dry bulb temperatures from 200 to 500 F and wet bulb temperatures from 100 to 210 F. Wet bulb temperature, adiabatic saturation temperature, dew point, relative humidity, steam content, and enthalpy of humid air streams are discussed. Graphs and a chart are presented that relate relative humidities and dry and wet bulb temperatures to equilibrium moisture content of wood. The practical problems relevant to evaluation and usage of psychrometric-equilibrium moisture content interactions are discussed and several areas of future research are suggested.

Keywords: Wet bulb temperature, dry bulb temperature, adiabatic saturation temperature, heat capacity, water vapor, air, vapor pressure, steam.

NOTATION

A	area of wetted surface, ft ²
c	heat capacity, Btu/lb °F
D _v	Water vapor diffusion coefficient, ft ² /h
h	heat transfer coefficient, Btu/h ft ² °F
H	enthalpy, Btu/lb dry air or Btu/lb water
ΔH _v	latent heat of vaporization, Btu/lb water
k	thermal conductivity, Btu/ft °F h
M	molecular weight, lb/lb mole
N _{Le}	Lewis number, k/cρD _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
Q	heat transfer, Btu/lb dry air
Q̇	heat transfer rate, Btu/h
RH	relative humidity, percent
SC	steam content, percent
T	temperature, °F
T̄	absolute temperature, °R
W	mass rate of evaporation, lb water/h
Y	humidity ratio based on T _{as} , lb water vapor/lb dry air
Y'	humidity ratio based on T _{wb} , lb water vapor/lb dry air

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κ	mass transfer coefficient, lb-mole water vapor/h ft ² psi
$\bar{\kappa}$	mass transfer coefficient, lb/h ft ² unit humidity difference
ρ	density, lb/ft ³

Subscripts

a	air
av	average
db	dry bulb
dp	dew point
f	air film
m	air-water vapor mixture
s	at adiabatic saturation temperature or saturation at adiabatic saturation temperature
t	total
T	at dry bulb temperature
w	water (liquid)
wb	at wet bulb temperature or saturation at wet bulb temperature
wv	water vapor

Psychrometry is a simple and inexpensive method to measure the relative amounts of air and water vapor in a humid air stream. The method requires measuring the actual air temperature (dry bulb temperature, T_{db}) as well as the temperature of a wetted "sock" from which water is vaporized into a gas (wet bulb temperature, T_{wb}). Worrall (1965) states that the psychrometer is well suited for measuring humidities up to temperatures of 500 F.

Until recently the forest products industry had little interest in psychrometric relationships and the influence of humidity on equilibrium moisture content of wood at temperatures above the boiling point of water. This interest has been encouraged recently for two reasons: first, the increased use of high temperature kilns to dry lumber and, second, the need for energy conservation in wood processing. Moisture content control, especially important when drying lumber for furniture stock, depends on maintaining a prescribed humidity in the kiln. Also, humidity determinations are required for evaluating energy use and for energy recovery potentials from lumber kilns and veneer dryers (Corder 1976; Rosen 1979).

Considerable experimental data have been presented to justify the theory for developing psychrometric charts below 210 F (Wengert and Mitchell 1979), but psychrometric charts for temperatures above 210 F have been based on an extension of the low temperature theory with very little experimental justification (Anon. 1976; Evans and Vaughan 1977; Zimmerman and Lavine 1964).

In this paper I derive the mathematical equations for calculating psychrometric charts, show the limitations of the equations, present high temperature psychrometric charts best suited for the conditions encountered in processing wood products (200–500 F T_{db} and 100–210 F T_{wb}), and present high temperature equilibrium moisture content (EMC) data from the literature. I also discuss the major gaps in psychrometric-EMC technology above 212 F and where the emphasis on research should be placed to fill these gaps.

DEVELOPMENT OF PSYCHROMETRIC CHARTS

Adiabatic saturation temperature

When unsaturated air is brought into contact with water, the air is humidified and cooled. If the system is operated so that no heat is gained or lost to the surroundings, the process is adiabatic. Thus, if the water remains at a constant temperature, the latent heat of evaporation must equal the sensible heat released by the air in cooling. If the temperature reached by the air when it becomes saturated is the same as the water, this temperature is called the *adiabatic saturation temperature*, T_s .

When air at temperature, T_{db} , and humidity, Y , is cooled to T_s (symbols are defined in the Notation section), the air will give up a quantity of heat, Q_1 ;

$$Q_1 = (H_a)_T + Y(H_{wv})_T - (H_a)_s - Y(H_{wv})_s. \quad (1)$$

As the air cools, its humidity increases from Y to Y_s at saturation, and the heat absorbed by the vaporization, Q_2 , is:

$$Q_2 = (Y_s - Y)[(H_{wv})_s - (H_w)_s]. \quad (2)$$

Because the process is adiabatic, $Q_1 = Q_2$, and after rearrangement:

$$Y = \frac{Y_s[(H_{wv})_s - (H_w)_s] + (H_a)_s - (H_a)_T}{(H_{wv})_T - (H_w)_s}. \quad (3)$$

Enthalpies are based on zero for liquid water at 32F [$(\Delta H_v)_{32} = 1,075.1$ Btu/lb]; thus

$$(H_{wv})_s = (\Delta H_v)_{32} + \int_{32}^{T_s} c_{wv} dT, \quad (4)$$

$$(H_{wv})_T = (\Delta H_v)_{32} + \int_{32}^{T_{db}} c_{wv} dT, \quad (5)$$

$$(H_a)_s - (H_a)_T = \int_{T_{db}}^{T_s} c_a dT, \text{ and} \quad (6)$$

$$(H_w)_s = \int_{32}^{T_s} c_w dT. \quad (7)$$

The humidity ratio corresponding to saturation at the adiabatic saturation temperature, Y_s , is related to the partial pressure of the water vapor at the adiabatic saturation temperature, p_s^* , for one atmosphere of total pressure (Zimmerman and Lavine 1964) by:

$$Y_s = \frac{0.6244 p_s^*}{(14.70 - p_s^*)}. \quad (8)$$

For the range of conditions from 100 to 212 F, partial pressure (Fig. 1) can be accurately related to T_s by:

$$p_s^* = 1.236 \times 10^7 \exp\left(-\frac{9,160}{T_s + 459.6}\right). \quad (9)$$

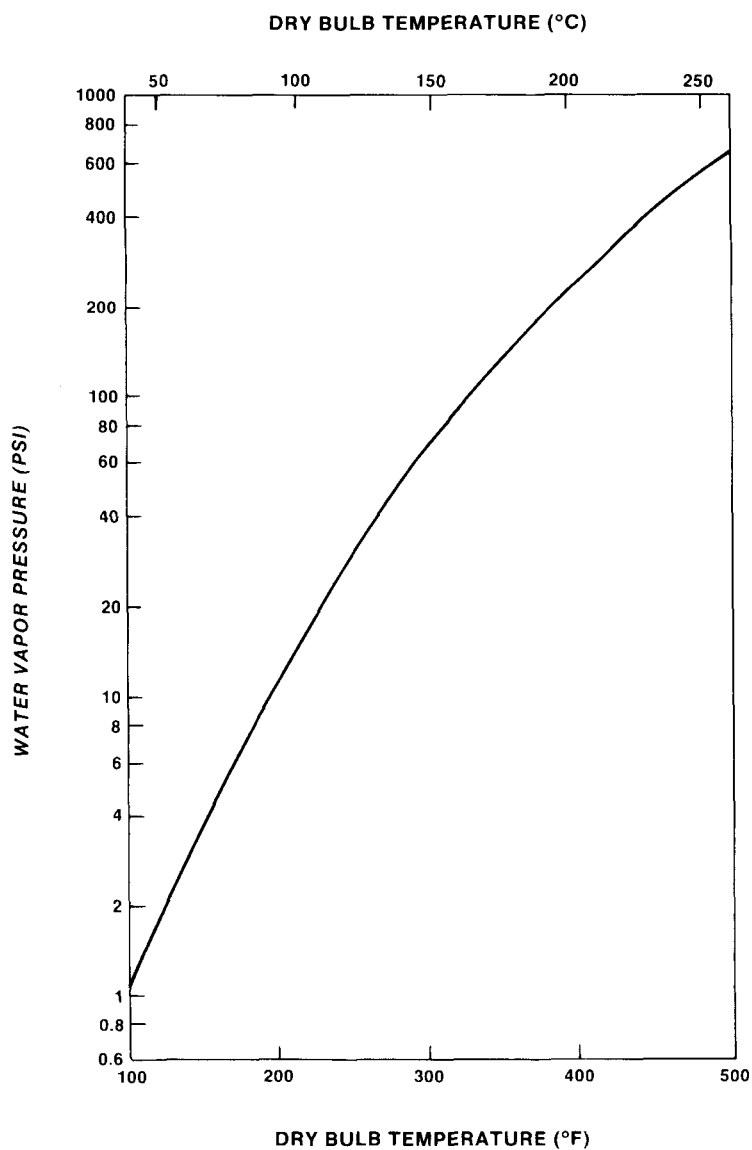


FIG. 1. Vapor pressure of water as a function of temperature (to convert psi to kPa, multiply by 6.895).

Values for c_{wv} , c_a , and c_w as a series function of temperature are obtained from the literature (Appendix).

The integrated forms of Eq. (4) to (7), as well as Eq. (8), were substituted into Eq. (3) to obtain Y as a function of $T_{(db)}$ and T_s .

Wet bulb temperature

Unsaturated air is passed over a wetted thermometer bulb such that water evaporates from the wetted surface causing the thermometer bulb to cool (Fig.

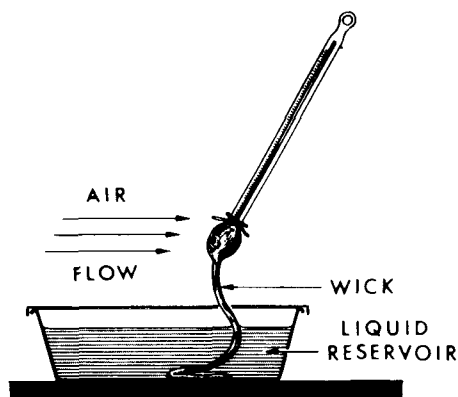


FIG. 2. Diagram of a wet bulb thermometer (Bennett and Myers 1962).

2). An equilibrium temperature, called the wet bulb temperature, T_{wb} , is reached when the rate of heat transfer from the wetted surface by convection and conduction is equal to the rate at which the wetted surface loses heat in the form of latent heat of evaporation. The rate of sensible heat transfer from the air to the wetted thermometer bulb, \dot{Q}_1 is:

$$\dot{Q}_1 = h_t A (T_{db} - T_{wb}). \quad (10)$$

The rate of heat loss by evaporation, which must diffuse through the air film that covers the wetted surface, is expressed by \dot{Q}_2 ;

$$\dot{Q}_2 = (\Delta H_v)_{wb} W \quad (11)$$

where

$$W = M_{wv} A \kappa (p_{wb}^* - p). \quad (12)$$

Humidity ratios can be determined from partial pressures with relationships similar to Eq. (8):

$$Y_{wb} = \frac{M_{wv} p_{wb}^*}{M_a (p_t - p_{wb}^*)} \quad (8a)$$

$$Y' = \frac{M_{wv} p}{M_a (p_t - p)}. \quad (8b)$$

Subtracting Eq. (8a) from (8b) and assuming that the partial pressure of water vapor is small compared to that of air, the following expression can be used (Treybal 1955):

$$(p_{wb}^* - p) \approx \frac{M_a p_t}{M_{wv}} (Y_{wb} - Y'). \quad (13)$$

Redefining κ in terms of a humidity difference, $\bar{\kappa} = M_a p_t \kappa$, and combining Eq. (11) to (13) yields:

$$\dot{Q}_2 = (\Delta H_v)_{wb} A \bar{\kappa} (Y_{wb} - Y') \quad (14)$$

at T_{wb} , $\dot{Q}_1 = \dot{Q}_2$. Thus,

$$Y' = Y_{wb} - \frac{h_f}{\bar{\kappa}(\Delta H_v)_{wb}}(T_{db} - T_{wb}). \quad (15)$$

The following empirical relationship was found to be true for dilute concentrations (Bennett and Myers 1962):

$$\frac{h_f}{\bar{\kappa}c_m} = (N_{Le})^{2/3} = \left(\frac{k}{c\rho D_v}\right)^{2/3}. \quad (16)$$

Combining Eq. (15) and (16):

$$Y' = Y_{wb} - \frac{(N_{Le})^{2/3}c_m}{(\Delta H_v)_{wb}}(T_{db} - T_{wb}). \quad (17)$$

Values of N_{Le} and c_m are functions of temperature and humidity (see Appendix) and $(\Delta H_v)_{wb}$ can be represented by (Zimmerman and Lavine 1964):

$$(\Delta H_v)_{wb} = 1,094 - 0.576T_{wb}. \quad (18)$$

We cannot obtain an explicit relationship between Y' , T_{db} , and T_{wb} . Thus, Eq. (17) must be solved by trial and error.

Figures 3 and 4 show plots of Eq. (3) and (17) for the range of conditions from 100 to 212 F T_{wb} and 200 to 500 F T_{db} .

Comparing Y and Y'

Equations (3) and (17) can be compared after some terms are redefined and certain assumptions are made.

Because the heat of vaporization at any given temperature (in this case at T_s) is merely the difference between the enthalpy of the water vapor and that of the water,

$$(\Delta H_v)_s = (H_{wv})_s - (H_w)_s \quad (19)$$

or rearranging Eq. (19)

$$(H_w)_s = (H_{wv})_s - (\Delta H_v)_s. \quad (20)$$

Equations (3) and (20) can be combined to yield

$$Y = \frac{Y_s(\Delta H_v)_s + (H_a)_s - (H_a)_T}{(\Delta H_v)_s + (H_{wv})_T - (H_{wv})_s}. \quad (21)$$

Average values of heat capacities in Btu/lb °F (0.24 for air and 0.46 for water) are substituted into Eq. (4) to (6), which after integration yield:

$$(H_{wv})_s = (\Delta H_v)_{32} + 0.46(T_s - 32), \quad (4a)$$

$$(H_{wv})_T = (\Delta H_v)_{32} + 0.46(T_{db} - 32), \text{ and} \quad (5a)$$

$$(H_a)_s - (H_a)_T = 0.24(T_s - T_{db}). \quad (6a)$$

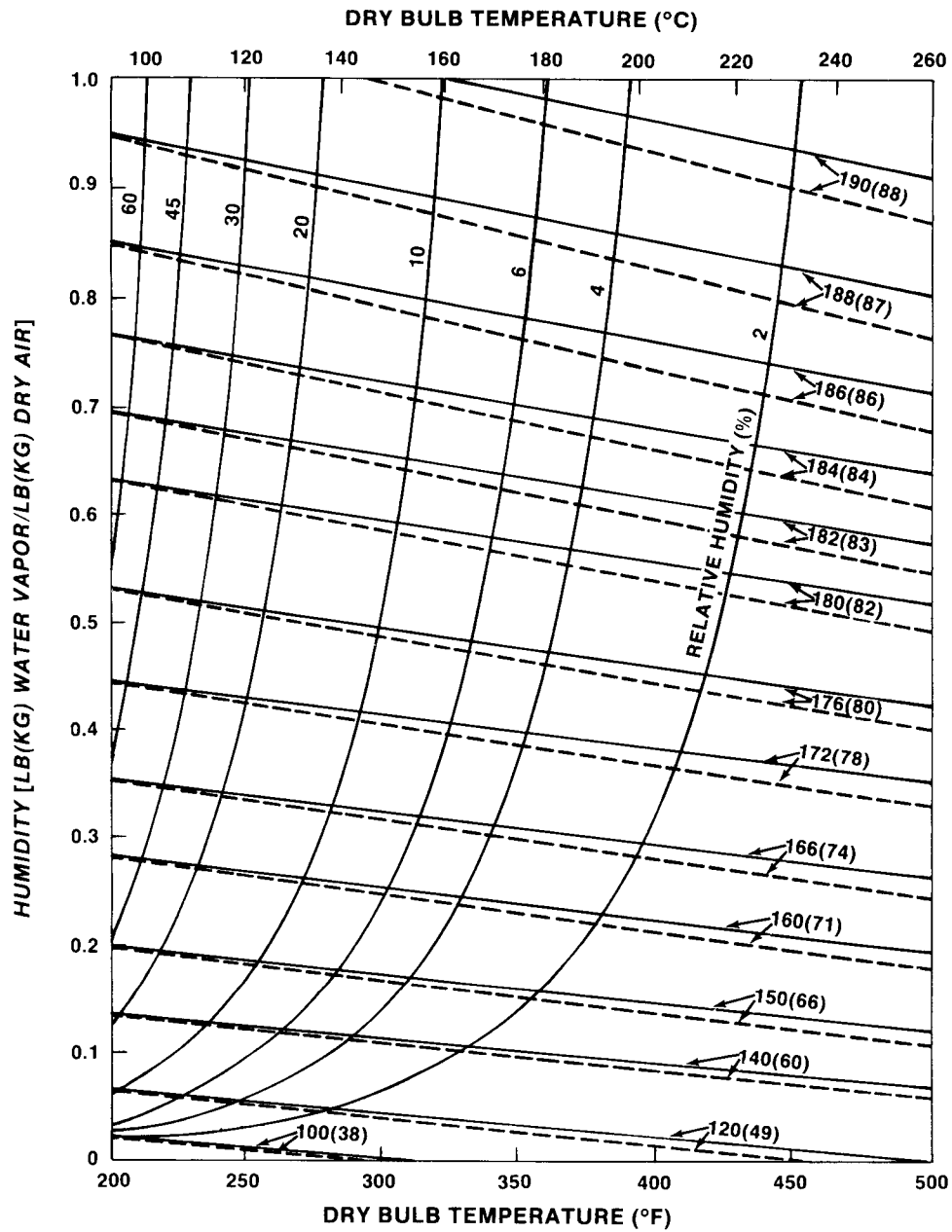


FIG. 3. Psychrometric chart for low humidity—solid horizontal lines are constant wet bulb temperature (°F/°C), dotted lines are constant adiabatic saturation temperature.

Equations (4a) to (6a) can be substituted into Eq. (21) to yield:

$$Y = Y_s - \frac{(0.24 + 0.46Y)}{(\Delta H_v)_s} (T_{db} - T_s). \quad (22)$$

Equation (22) is in the same form as Eq. (17) and the two are identical for $N_{Le} =$

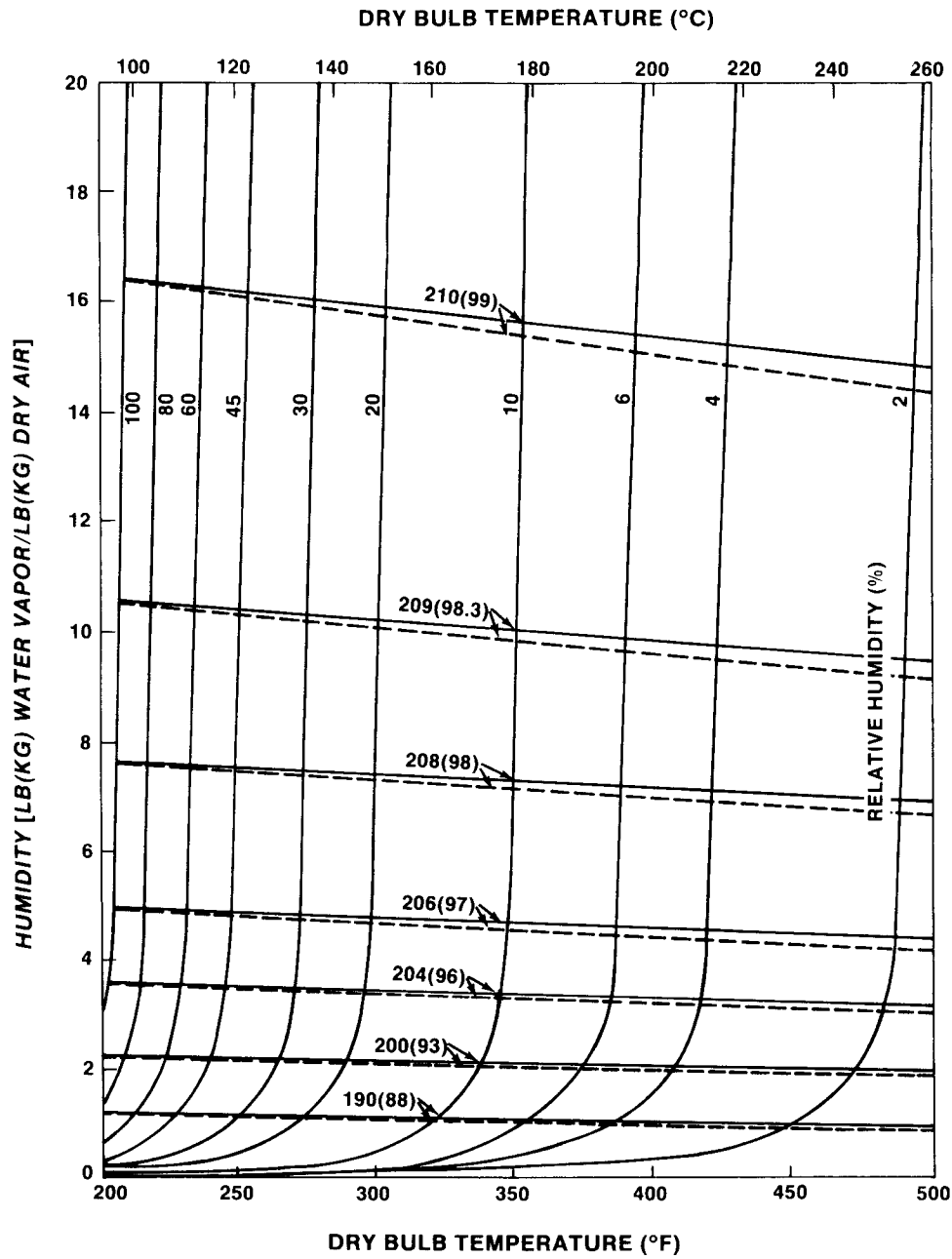


FIG. 4. Psychrometric chart for high humidity—solid horizontal lines are constant wet bulb temperature (°F/°C), dotted lines are constant adiabatic saturation temperature.

1.0 and $c_m = 0.24 + 0.46Y$, if Y' and T_{wb} are substituted for Y and T_s , respectively.

Because T_{wb} rather than T_s is usually measured in practical application, further concepts will be based on Y' rather than Y .

Dew point temperature, T_{dp}

The dew point is the temperature at which a given sample of moist air becomes saturated as it is cooled at constant pressure. Dew point temperatures can be evaluated by constructing a horizontal line on a psychrometric chart from a point corresponding to the original temperature and humidity to a point with the same humidity on the 100% saturation curve. The dew point also can be calculated directly by rearranging Eq. (9) and substituting p_{wb}^* and T_{dp} for P_s^* and T_s , respectively, if the humidity ratio, Y' , is known:

$$T_{dp} = \frac{9,160}{16.33 - \ln p_{wb}^*} - 459.6 \quad (23)$$

where

$$p_{wb}^* = \frac{14.70Y'}{0.6244 + Y'}$$

A large difference exists between T_{dp} and T_{wb} , especially at T_{wb} below 160 F (Fig. 5).

Relative humidity, RH/steam content, SC

Relative humidity expressed on a percentage basis is defined by:

$$RH = \frac{p}{p^*} \times 100. \quad (24)$$

Above 212 F at atmospheric pressure, RH must be less than 100% because the maximum value for p is 1 atmosphere and p^* must be greater than 1 atmosphere. At 500 F, for example, the maximum relative humidity is only 2.2%.

A useful concept called the steam content, SC, is helpful when describing high temperature environments (Sturney 1952):

$$SC = \frac{p}{p_t} \times 100. \quad (25)$$

Constant SC lines are thus lines of constant partial water vapor pressure and are coincident with dew point lines.

Combining Eq. (24) and (25), at atmospheric pressure,

$$RH = \frac{14.7}{p^*} SC. \quad (26)$$

Thus, the 100% SC line gives the greatest RH that can exist at each temperature.

Enthalpy, H

Enthalpy, or heat content of a substance, is generally defined as the difference between the enthalpy at some temperature and at some arbitrary temperature (32 F in this paper). The enthalpy of a humid air steam, H , is thus

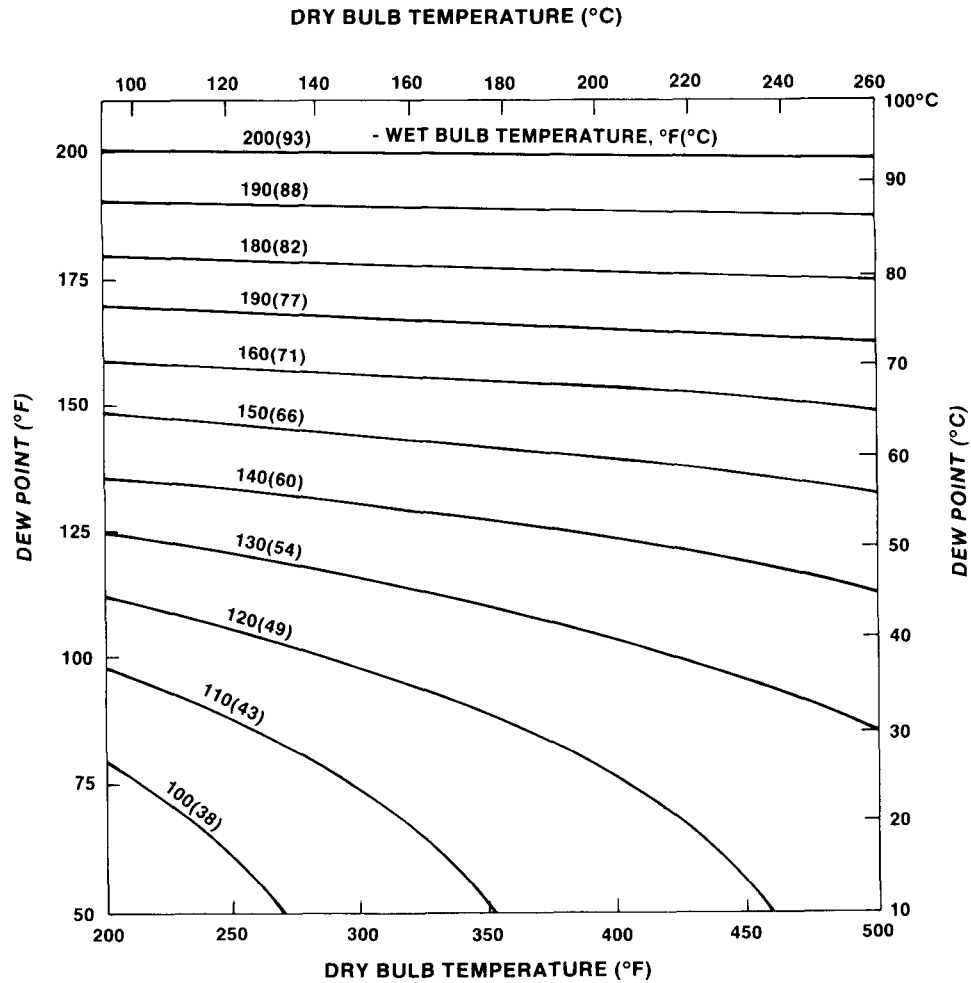


FIG. 5. Dew point temperature as related to wet and dry bulb temperature.

$$H = (H_a)_T + Y'(H_{wv})_T \quad (27)$$

$$H = \int_{32}^{T_{db}} c_a dT + Y'[(\Delta H_v)_{32} + \int_{32}^{T_{db}} c_{wv} dT]. \quad (28)$$

Substituting the values of c_a and c_{wv} from the Appendix, and Y' from Eq. (17), H can be evaluated from Eq. (28) for the range of T_{db} and T_{wb} . For a constant wet bulb temperature, the change in enthalpy from 200 to 500 F dry bulb temperature was found to be small. As dry bulb temperature increased, the increase in sensible heat of the humid air was approximately equal to the decrease in latent heat due to a decrease in humidity. The values of H as a function of wet bulb temperature at 300 F dry bulb temperature are plotted in Fig. 6. At a given wet bulb temperature, H for any dry bulb temperature between 200 and 500 F is within 1.5% of that value in Fig. 6.

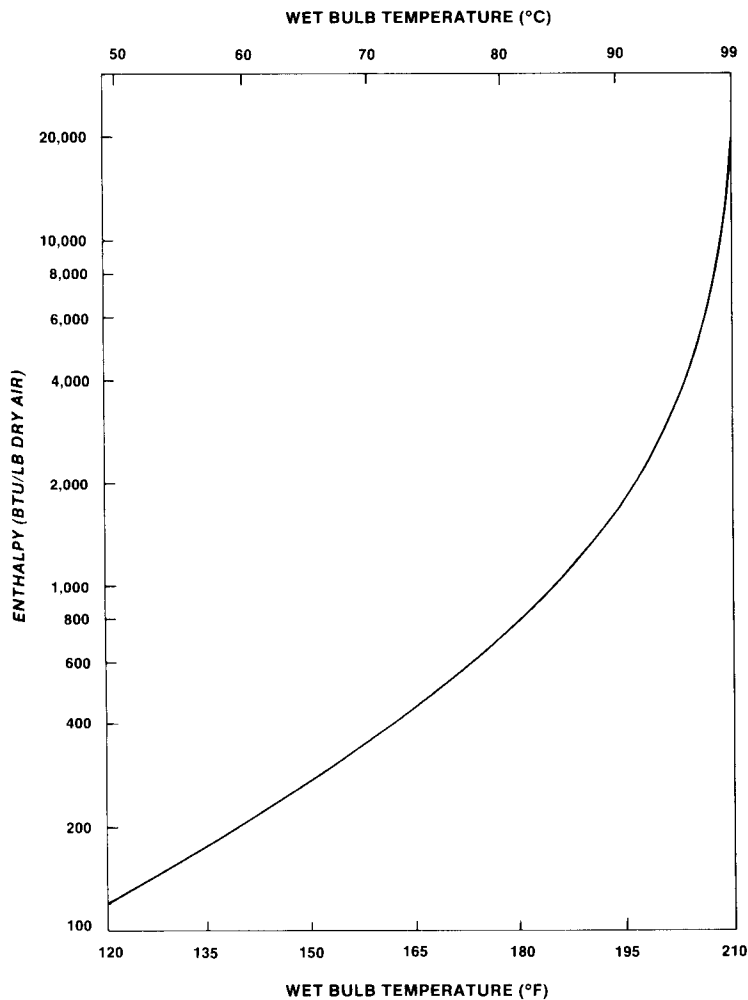


FIG. 6. Enthalpy of humid air streams as a function of wet bulb temperature for 300 F dry bulb temperature (to convert Btu/lb to kJ/kg, multiply by 2.325).

THE RELATIONSHIP OF EMC TO WET AND DRY BULB TEMPERATURE

Much of the basic data and mathematical techniques for evaluating EMC at temperatures above 212 F were developed in the late 1940's and early 1950's in Germany and Australia (Kauman 1956; Kollman 1961). Until recently, the only EMC data available above 212 F were for pure superheated steam at atmospheric conditions (Fig. 7 and Hann 1965). The pure superheated steam curve ($T_{wb} = 212$ F) represents the maximum EMC attainable at each dry bulb temperature. Above 212 F, EMC drops rapidly with increasing temperature to less than 3% at 275 F. Rosen (1978, 1980) has presented EMC values for wood in air-steam mixtures (Fig. 8).

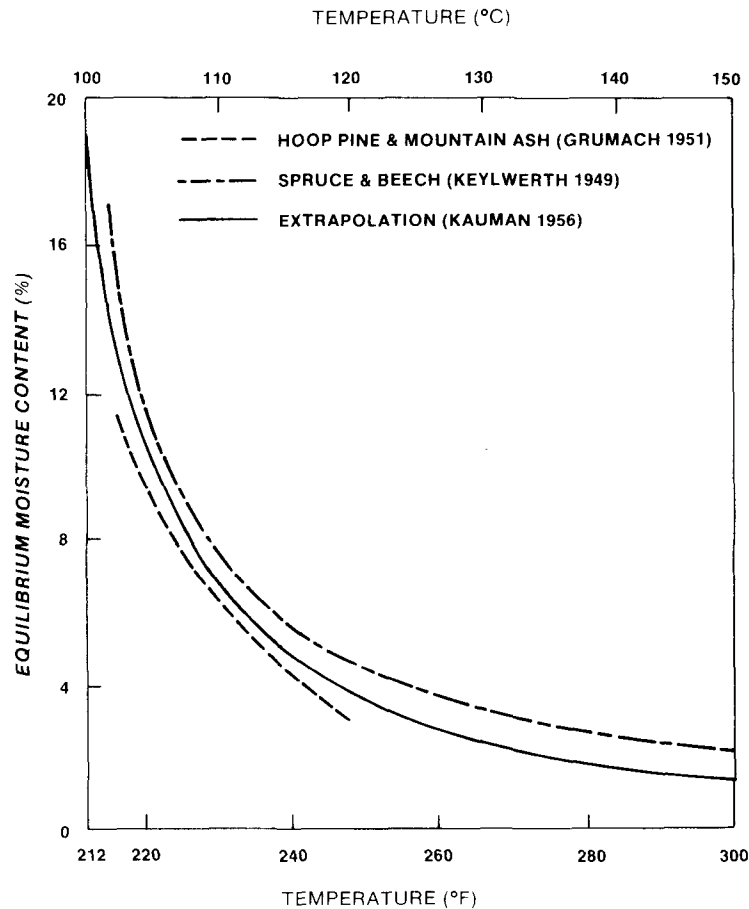


FIG. 7. Equilibrium moisture content values for wood in pure superheated steam at atmospheric pressure (Grumach 1951; Keylwerth 1949; Kauman 1956).

The charts and tables in the literature (Kauman 1956; Ladell 1957) relating EMC to conditions in humid air streams above 212 F at atmospheric pressure are based on an extrapolation technique (Table 1). Stamm and Loughborough (1935) observed from desorption isotherm data (Fig. 9) that a plot of the logarithm of water vapor pressure against the reciprocal of absolute temperature (isosteres) for each of a number of different moisture contents yielded a straight line (Fig. 10). Extension of the isosteres to temperatures above 212 F agrees within 1% moisture content of experimental data in pure superheated steam (Fig. 7).

To illustrate the use of Fig. 10 and psychrometric charts for determining EMC from measurements of T_{db} and T_{wb} , find the EMC at T_{db} of 223 F and T_{wb} of 200 F. At these conditions, the relative humidity is 60% (Fig. 4). The saturated vapor pressure of water at T_{db} of 223 F is 18.3 (Fig. 1). Calculating the vapor pressure of water from Eq. (24):

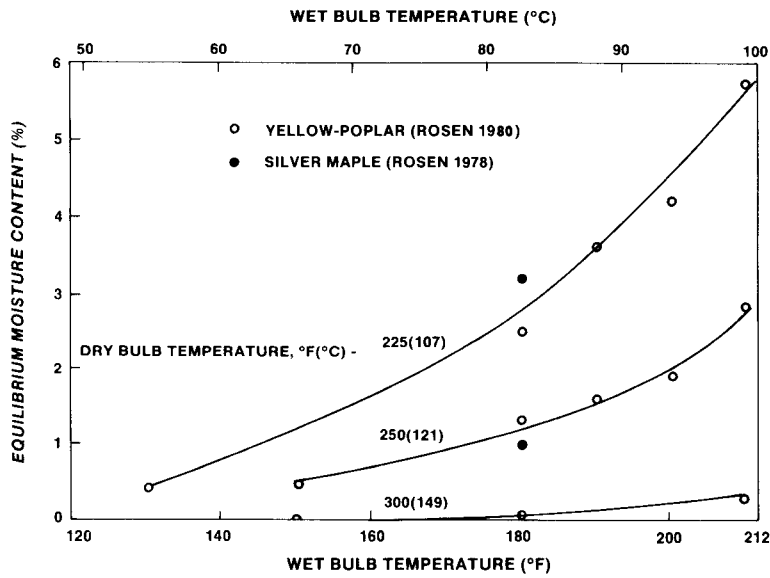


FIG. 8. Equilibrium moisture content of wood in air-water vapor mixtures. The points are based on the average of 7 to 12 values (Rosen 1978, 1980).

$$p = 18.3 \times \frac{60}{100} = 11.0.$$

Thus, EMC = 6.2% (Fig. 10).

Several investigations also showed the extrapolation technique could be used to evaluate EMC for pressures other than atmospheric above 212 F (Czepek 1952;

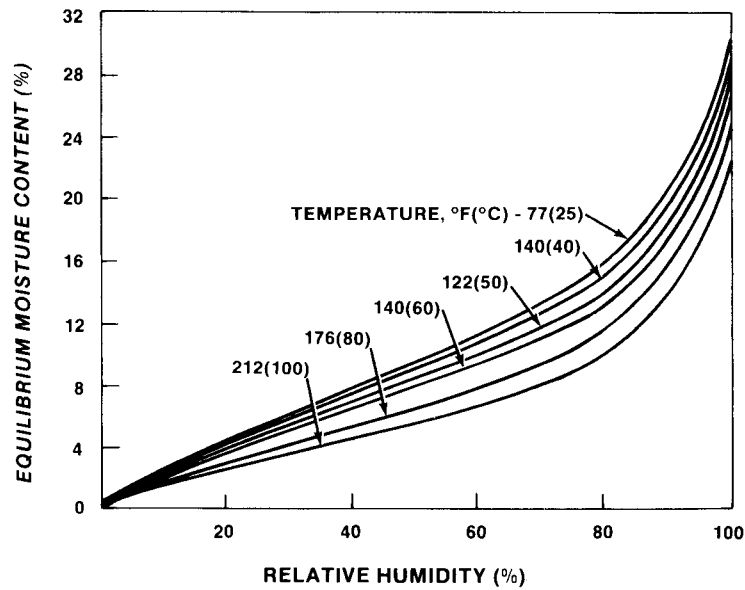


FIG. 9. Desorption isotherms at several temperatures for Sitka spruce (Stamm 1964).

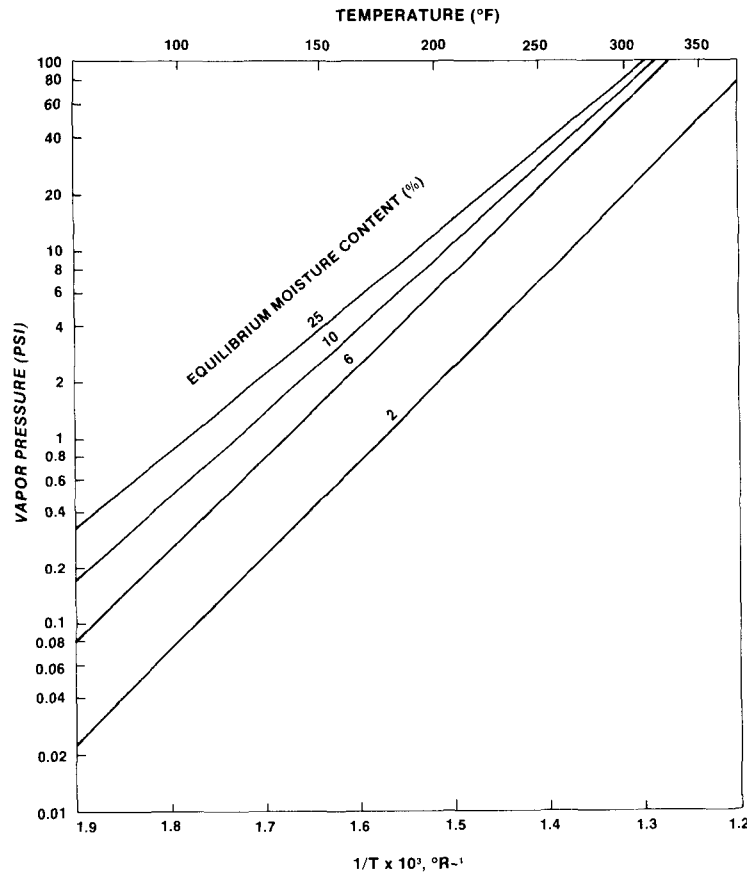


FIG. 10. Extrapolation of vapor pressure versus temperature for several EMC's.

Kauman 1956; Keylwerth and Noack 1964; Kröll 1951) (Fig. 11). Equilibrium moisture content data for a range of pressures and temperatures above 212 F are given in several adsorption isotherm studies (Engelhardt 1979; Noack 1959; Strickler 1968). Interpretation of EMC data at the higher temperatures is complicated by partial thermal degradation and loss of wood mass, but investigators have shown methods to correct for this loss. Separate investigators found big differences in EMC values, especially above 80% relative humidity, as typified by the 338 F isotherms (Fig. 12). Differences in experimental technique and wood species might account for the disparity.

PROBLEMS IN PRACTICAL USAGE OF PSYCHROMETRIC-EMC INFORMATION

Accurate measurement of wet bulb temperatures is more difficult at dry bulb temperatures above 212 F than below 212 F. The design of the wet bulb thermometer and wick must be such that the surface of the bulb remains wet and adequate humid air is circulated across the wick to ensure that all the heat of evaporation of water from the wick is transferred as sensible heat to the humid

TABLE 1. High-temperature relative humidity and equilibrium moisture content table (Kauman 1956; Ladell 1957).

Dry bulb temperature, °F/°C	Wet bulb temperature, °F/°C										
	150/66	160/71	170/77	180/82	190/88	195/91	200/93	205/96	210/99	212/100	
200/93	3.3 ¹ (32) ²	4.2 (41)	5.3 (51)	6.9 (62)	10.8 (79)	14.7 (90)	20.3 (100)				
205/96	2.8 (29)	3.7 (37)	4.6 (46)	5.9 (57)	8.1 (70)	10.8 (80)	15.0 (91)	20.0 (100)			
210/99	2.6 (26)	3.3 (33)	4.0 (41)	5.0 (51)	6.6 (63)	8.4 (72)	10.8 (81)	14.5 (91)	19.7 (100)		
215/102	2.4 (24)	2.9 (30)	3.5 (38)	4.5 (47)	5.7 (58)	7.0 (66)	8.7 (74)	10.7 (82)	14.0 (90)	15.5 (94)	
220/104	2.1 (22)	2.6 (27)	3.2 (34)	3.9 (42)	5.0 (52)	5.9 (61)	6.9 (67)	8.3 (74)	10.4 (82)	11.3 (85)	
225/107	1.9 (20)	2.3 (25)	2.8 (31)	3.4 (38)	4.3 (48)	5.1 (56)	5.8 (62)	6.6 (67)	8.0 (64)	8.7 (77)	
230/110	1.7 (18)	2.1 (23)	2.5 (28)	3.1 (35)	3.8 (44)	4.5 (51)	4.9 (55)	5.5 (61)	6.3 (67)	6.9 (70)	
235/113	1.5 (16)	1.9 (21)	2.3 (26)	2.7 (31)	3.4 (40)	3.9 (46)	4.3 (51)	4.7 (55)	5.4 (61)	5.8 (65)	
240/116	1.3 (14)	1.7 (19)	2.1 (24)	2.5 (29)	3.1 (37)	3.5 (42)	3.8 (46)	4.2 (51)	4.7 (56)	5.0 (59)	
250/121	1.0 (12)	1.3 (16)	1.6 (20)	2.0 (24)	2.4 (30)	2.8 (35)	3.1 (39)	3.4 (43)	3.6 (47)	3.8 (49)	
260/127	0.8 (10)	1.0 (13)	1.3 (17)	1.6 (20)	2.0 (26)	2.2 (30)	2.4 (33)	2.7 (36)	2.9 (40)	3.1 (42)	
275/135	0.5 (8)	0.7 (10)	0.9 (13)	1.1 (16)	1.4 (20)	1.7 (23)	1.9 (26)	2.1 (29)	2.3 (31)	2.4 (32)	
300/149	0.1 (5)	0.2 (7)	0.3 (9)	0.4 (11)	0.5 (13)	0.7 (15)	0.9 (17)	1.1 (19)	1.3 (21)	1.4 (22)	

¹ Equilibrium moisture content for Sitka spruce.² Relative humidity—air-water vapor mixtures at atmospheric pressure.

air. Wet bulb sensing devices that are adequate for low temperature operations are not necessarily adequate for high temperature operations.

Many of the psychrometric charts and tables in the literature assume that the adiabatic saturation and wet bulb temperatures are equal and neglect the change in properties of the physical parameters with temperature and humidity. Thus, humidities are calculated from relationships similar to Eq. 22. Figures 3 and 4 clearly show a difference between humidities evaluated at the same T_s and T_{wb} at T_{db} above 200 F. Even though the analysis of this paper takes into account the changes in physical parameters with changing conditions, several relationships [such as Eq. (13) and (16)] need to be examined more carefully for high humidities. Because there is minimal experimental verification of psychrometric relationship above 212 F, the best mathematical approach for describing the interaction of Y' , T_{db} , and T_{wb} will remain arbitrary.

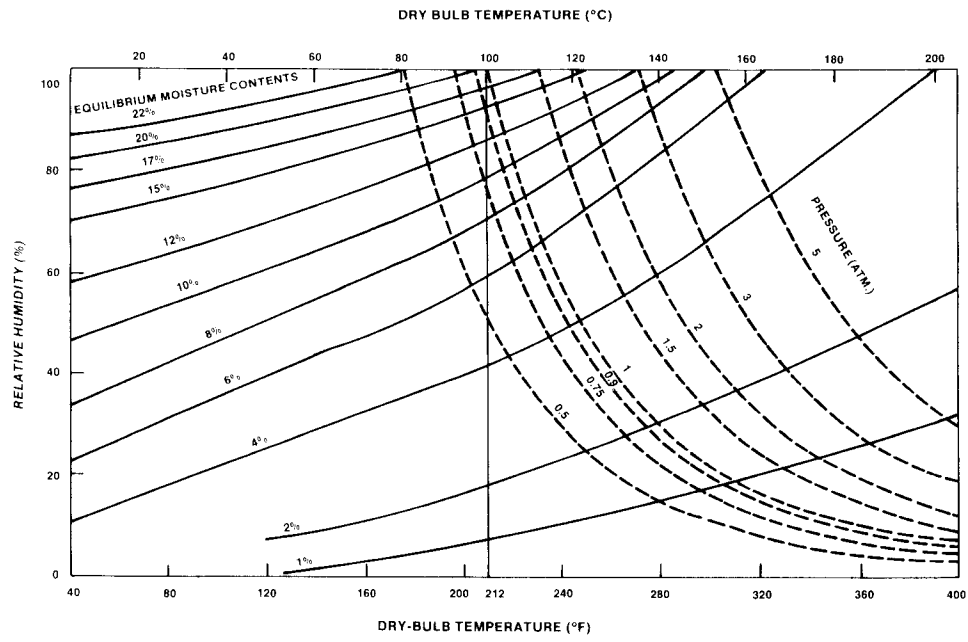


FIG. 11. Equilibrium moisture content of wood and 100% steam content lines at various total pressures (Kauman 1956).

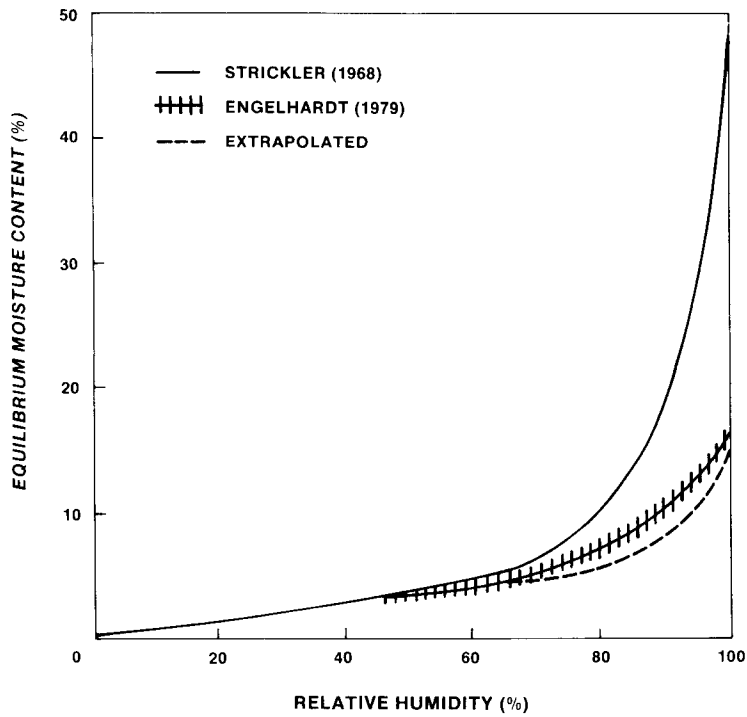


FIG. 12. Comparison of experimental and extrapolated isotherms at 338 F.

The lack of EMC data and differences in existing EMC data above 212 F constitute a major problem. Although the isostere extrapolations fit well for pure superheated steam at atmospheric pressure, they predict high for air-steam mixtures (compare values from Table 1 with those of Fig. 8).

RECOMMENDATIONS FOR FUTURE RESEARCH

1. A simple, economical, and accurate method to measure humidity in air-water vapor mixtures at temperatures above 212 F should be developed.
2. Experimental verification of psychrometric charts above 212 F dry bulb temperature should be undertaken.
3. Experimental values of EMC as a function of temperature above 212 F, humidity, and total pressure (especially at one atmosphere) should be obtained.

APPENDIX

- I. Heat capacities of components as a function of temperature.

$$c_a = 0.2317 + 9.01 \times 10^{-6}\bar{T} + 1.22 \times 10^{-8}\bar{T}^2 - 2.78 \times 10^{-12}\bar{T}^3$$

$$c_{wv} = 0.427 + 1.416 \times 10^{-5}\bar{T} + 4.318 \times 10^{-8}\bar{T}^2 - 8.171 \times 10^{-12}\bar{T}^3$$

where c_a and c_{wv} are in Btu/lb °F and \bar{T} is in °R (Hougan et al. 1959)

$$c_w = 0.991 + 8.04 \times 10^{-5}T$$

where c_w is a linear fit of the data from 100 to 212 F and T is in °F (Perry 1963).

- II. Evaluation of the Lewis Number (N_{Le}) and humid heat (c_m).

The Lewis $\left(\frac{k}{c_p D_v}\right)$ numbers for the air-water vapor mixtures were evaluated at the average condition of wet and dry bulb temperature,

$$T_{av} = \frac{T_{wb} + T_{db}}{2}$$

Density ρ_m (lb/ft³)

From the ideal gas law,

$$\rho_m = \frac{1 + Y'}{(T_{av} + 459.6)(0.0252 + 0.0407Y')}$$

heat capacity or humid heat, c_m (Btu/lb °F)

based on average values of heat capacities of air and water vapor over T_{av} from 150 to 355 F

$$c_m = 0.243 + 0.455Y'$$

Diffusion coefficient, D_v (ft²/h)

From a linear fit of the data presented by Evans and Vaughan (1977)

$$D_v = 0.663 + 4.03 \times 10^{-3}T_{av}$$

Thermal conductivity, k_m (Btu/h ft °F)

The thermal conductivity of the components

$$k_{wv} = 0.0083 + 2.5 \times 10^{-5}T_{av} \text{ (Weast 1966)}$$

$$k_a = 0.0132 + 2.39 \times 10^{-5}T_{av} \text{ (Bennett and Myers 1962)}$$

were used to estimate the thermal conductivity of the moisture as described by Bird et al. (1960).

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