(905212)Chemical Engineering Principles (2)

CHAPTER 8:
Balances on Nonreactive Processes

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Estimation of Heat Mixture

•Estimation of Cp for **solids, liquids around 20 ^{0}C**: use Kopp's Rule (Section 8.3c and Table B.10). Use when you can't find the data in Table B.2.

$$(C_p)_{Ca(OH)_2} = (C_{pa})_{Ca} + 2(C_{pa})_O + 2(C_{pa})_H$$
$$= [26 + (2 \times 17) + (2 \times 9.6)]\ J/(mol \cdot {}^\circ C) = 79\ J/(mol \cdot {}^\circ C)$$

[The true value is 89.5 J/(mol·°C).]

$$(C_p)_{mix}(T) = \sum_{\substack{\text{all} \\ \text{mixture} \\ \text{components}}} y_i C_{pi}(T) \qquad \textbf{(8.3-13)}$$

where

$(C_p)_{mix}$ = heat capacity of the mixture
y_i = mass or mole fraction of the ith component
C_{pi} = heat capacity of the ith component

Heat Capacity of a Mixture

Calculate the heat required to bring 150 mol/h of a stream containing 60% C_2H_6 and 40% C_3H_8 by volume from 0°C to 400°C. Determine a heat capacity for the mixture as part of the problem solution.

$$(C_p)_{\text{mix}}[\text{kJ/(mol}\cdot{}^\circ\text{C)}] = 0.600(0.04937 + 13.92 \times 10^{-5}T - 5.816 \times 10^{-8}T^2 + 7.280 \times 10^{-12}T^3)$$

$$+ 0.400(0.06803 + 22.59 \times 10^{-5}T - 13.11 \times 10^{-8}T^2 + 31.71 \times 10^{-12}T^3)$$

$$= 0.05683 + 17.39 \times 10^{-5}T - 8.734 \times 10^{-8}T^2 + 17.05 \times 10^{-12}T^3$$

$$\Delta\hat{H} = \int_{0^\circ\text{C}}^{400^\circ\text{C}} (C_p)_{\text{mix}}\, dT = 34.89 \text{ kJ/mol}$$

$$\dot{Q} = \Delta\dot{H} = \dot{n}\,\Delta\hat{H} = \frac{150 \text{ mol}}{\text{h}} \left| \frac{34.89 \text{ kJ}}{\text{mol}} \right. = \boxed{5230 \frac{\text{kJ}}{\text{h}}}$$

8.4b Latent heat correlations

Heat of vaporization $\Delta\hat{H}_v$

Trouton's rule:

$$\Delta\hat{H}_v(\text{kJ/mol}) \approx 0.088T_b(\text{K}) \quad \text{(nonpolar liquids)}$$
$$\approx 0.109T_b(\text{K}) \quad \text{(water, low molecular weight alcohols)} \qquad \textbf{(8.4-3)}$$

Chen's equation:

$$\Delta\hat{H}_v(\text{kJ/mol}) = \frac{T_b[0.0331(T_b/T_c) - 0.0327 + 0.0297 \log_{10} P_c]}{1.07 - (T_b/T_c)} \qquad \textbf{(8.4-4)}$$

where T_b and T_c are the normal boiling point and critical temperature in kelvin and P_c is the critical pressure in atmospheres.

Clausius–Clapeyron

$$\ln p^* = -\frac{\Delta\hat{H}_v}{RT} + B \qquad \textbf{(8.4-6)}$$

(See Example 6.1-1.)

Clapeyron equation

$$\frac{d(\ln p^*)}{d(1/T)} = -\frac{\Delta\hat{H}_v}{R} \qquad \textbf{(8.4-7)}$$

Watson's correlation:

$$\Delta\hat{H}_v(T_2) = \Delta\hat{H}_v(T_1)\left(\frac{T_c - T_2}{T_c - T_1}\right)^{0.38} \qquad \textbf{(8.4-8)}$$

where T_c is the critical temperature of the substance

Heat of fusion

A formula for approximating a standard heat of fusion is

$$\Delta\hat{H}_m(\text{kJ/mol}) \begin{cases} \approx 0.0092T_m(\text{K}) & \text{(metallic elements)} \\ \approx 0.0025T_m(\text{K}) & \text{(inorganic compounds)} \\ \approx 0.050T_m(\text{K}) & \text{(organic compounds)} \end{cases} \qquad \textbf{(8.4-5)}$$

Example 8.4.3

Estimation of a Heat of Vaporization

- The normal boiling point of methanol is 337.9 K, and the critical temperature of this substance is 513.2 K. Estimate the heat of vaporization of methanol at 200°C.

We first use Trouton's rule to estimate $\Delta\hat{H}_v$ at the normal boiling point, and then Watson's correlation to estimate $\Delta\hat{H}_v(473\text{ K})$ from $\Delta\hat{H}_v(337.9\text{ K})$.

Trouton's Rule $\Delta\hat{H}_v(337.9\text{ K}) = (0.109)(337.9) = 36.8\text{ kJ/mol}$

(The measured value is 35.3 kJ/mol. Chen's equation yields 37.2 kJ/mol, so in this unusual case Trouton's rule provides the better estimate.)

Watson's Correlation

Using the value of $\Delta\hat{H}_v$ estimated by Trouton's rule

$$\Delta\hat{H}_v(473\text{ K}) = 36.8\left(\frac{513.2 - 473}{513.2 - 337.9}\right)^{0.38} = \boxed{21.0\text{ kJ/mol}}$$

The measured value is 19.8 kJ/mol.

Psychrometric Chart or Humidity Chart

a. **Dry bulb temperature:** Temperature as measured by a thermometer, thermocouple, etc.

b. **Absolute humidity**: h_A (lb_m H_2O/lb_m DA) (also called moisture content). In terms of this quantity, the mass fraction of water is $y_i = \frac{h_a}{1+h_a}$

c. **Relative humidity**: $h_r = 100 \frac{p_{H2O}}{p_{H2O}^*(T)}$

d. **Dew point temperature**: Temperature at which humid air becomes saturated if cooled at constant pressure. Follow any point horizontally to the left until you reach the saturation curve.

e. **Humid volume:** $\hat{V}_H(m^3 / kg\ DA)$ - volume accompanied by 1 lb_m DA plus the water vapor that accompanies it

f. **Wet bulb temperature**: T_{wb} – temperature reading on a thermometer with a water-saturated wick around the bulb immersed in a flowing stream of humid air. (*Why do you feel cold when you step out of the shower or pool?)*

g. **Specific enthalpy of saturated air**: Btu/lb_m DA

h. **Enthalpy deviation**: Used to determine the enthalpy of humid air that is not saturated. Subtract enthalpy deviation from specific enthalpy of saturated air, which you find by following the wet bulb temperature line to the saturation line.

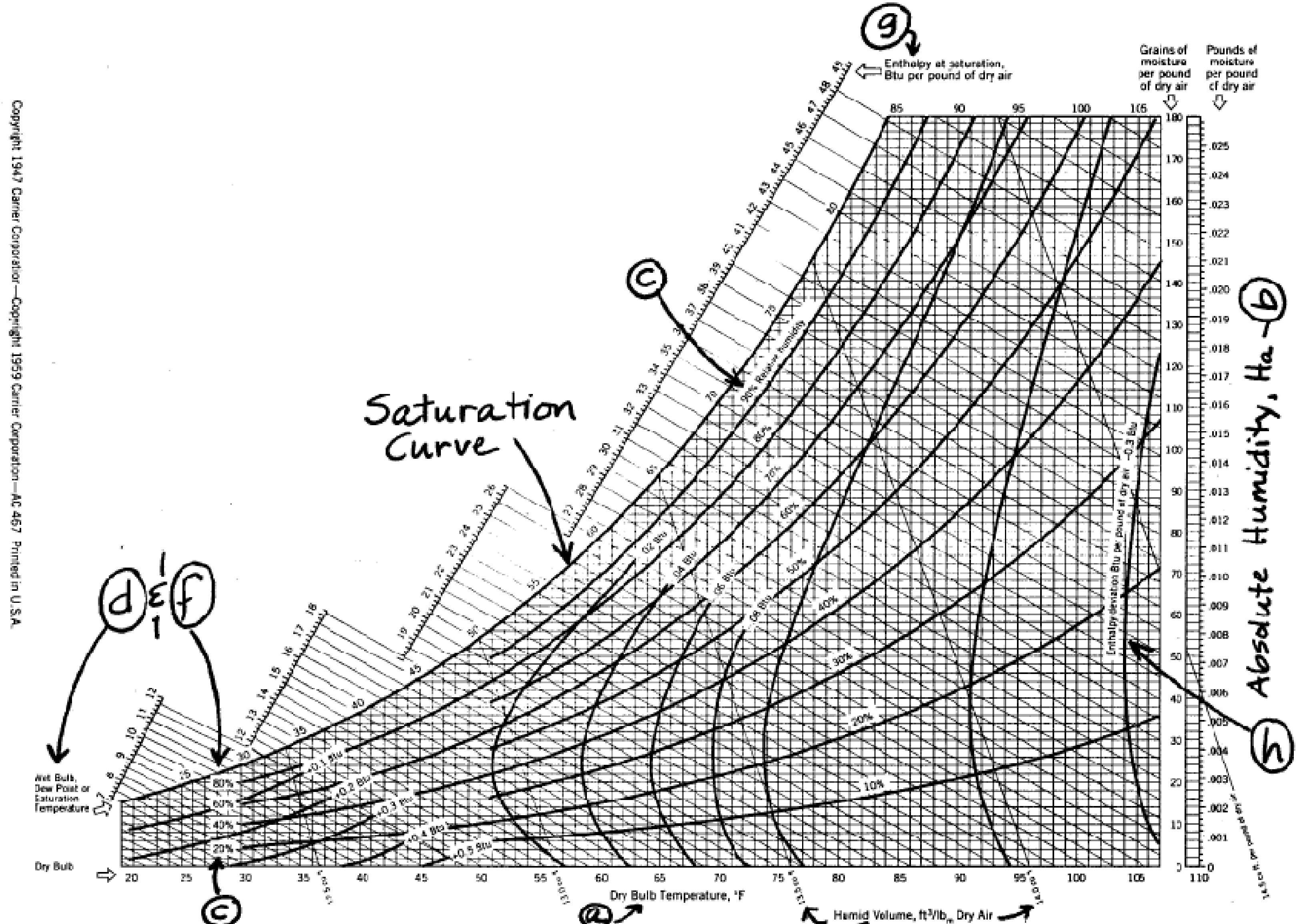

Figure 8.4-2 Psychrometric chart—American Engineering units. Reference states: H_2O (L, 32°F, 1 atm), dry air (0°F, 1 atm). (Reprinted with permission of Carrier Corporation.)

Psychrometric Chart or Humidity Chart

Several properties of gas-vapor mixture are cross plotted, provided a concise compilation of a large quantity of physical property data.

The most common of these charts –that for air-water system at 1 atm-is used extensively in the analysis of humidification, drying, and air-conditioning processes.

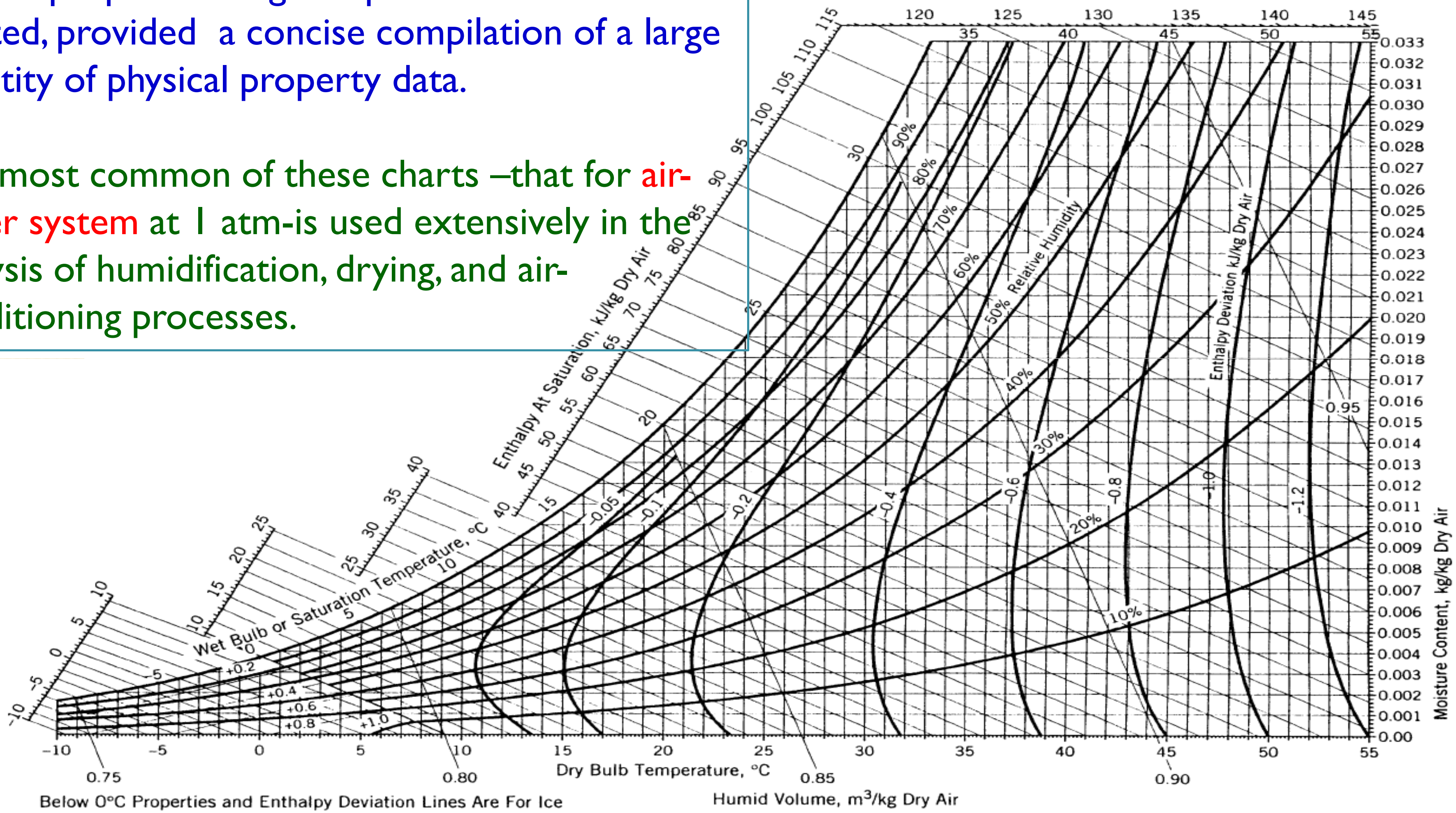

Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Psychrometric Chart or Humidity Chart

Dry-bulb temperature (T_{db}): The abscissa of the chart. T_{db} is the air temperature as measured by thermometer, TC or other suitable device

Absolute humidity, h_a [kg H_2O(v)/DA]: The moisture content-the ordinate of the chart.

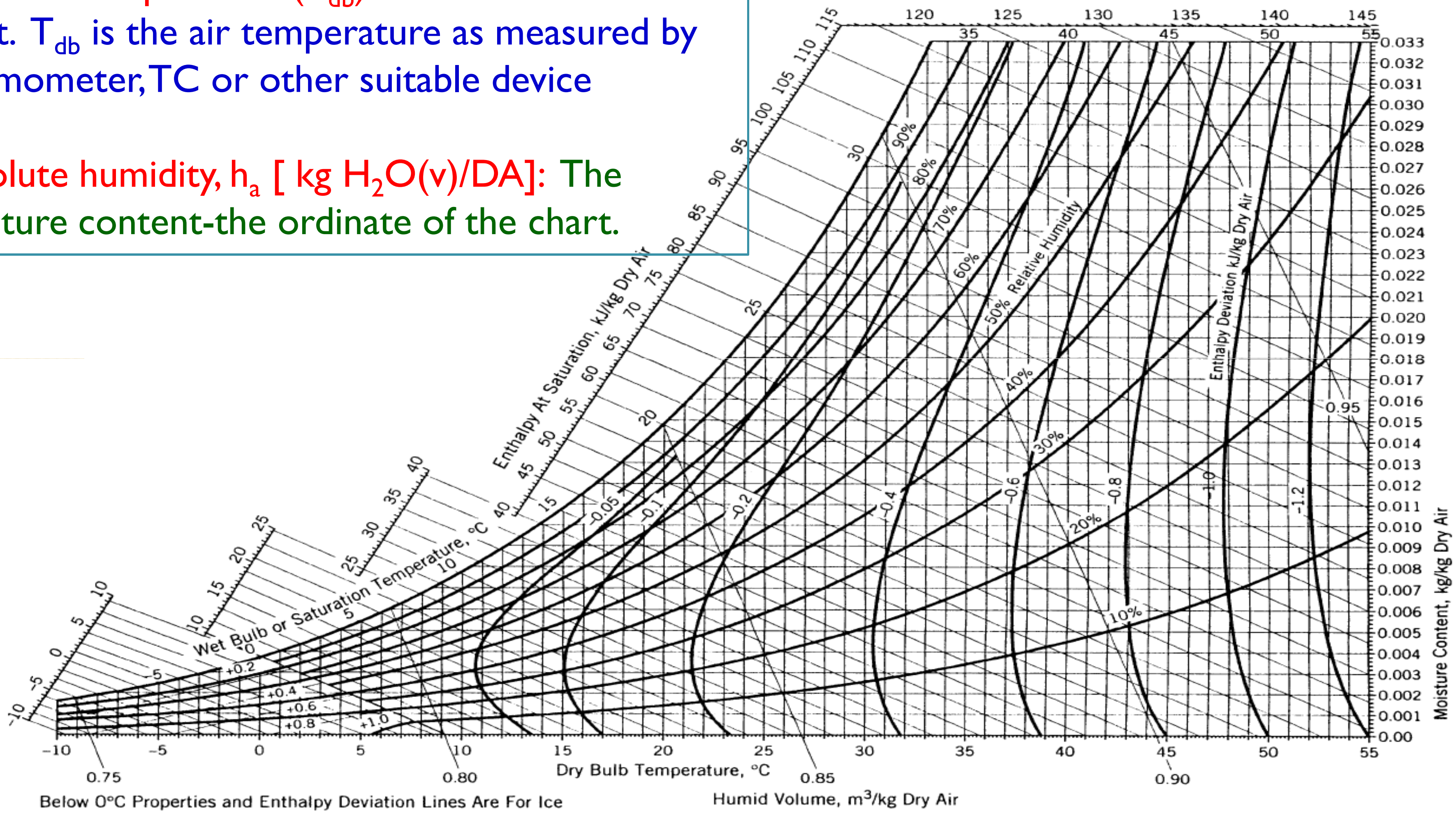

Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Psychrometric Chart or Humidity Chart

Relative humidity , h_r = [100 x $P_{H2O}/P^*_{H2O}(T)$]:
Represents as %

Dew point, T_{dp}: The temperature at which humid air becomes saturated if it is cooled at constant pressure.

<u>What the T_{dp} of humid air at 30 °C and h_r = 20 %?</u>

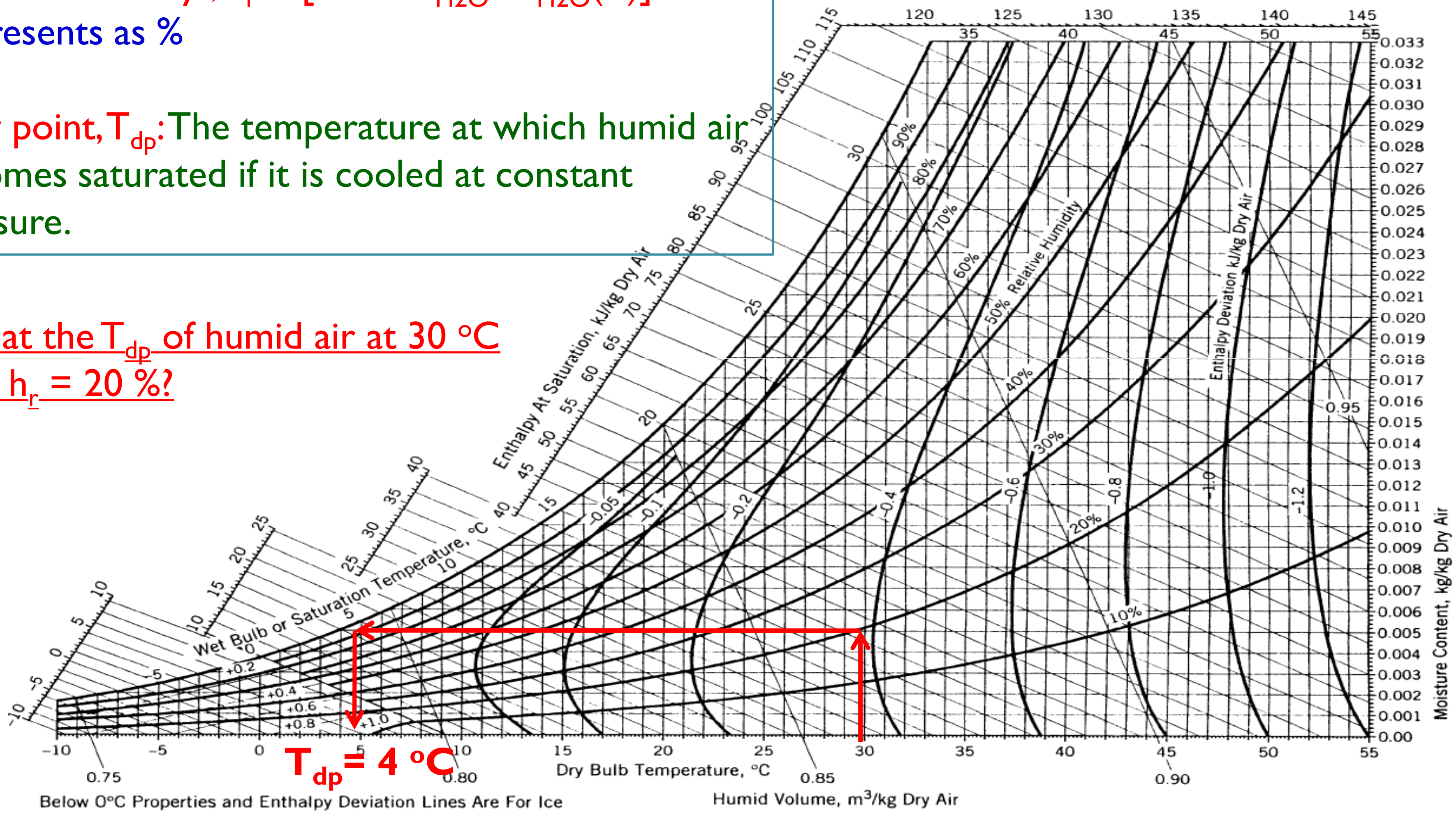

Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Psychrometric Chart or Humidity Chart

Humid volume, v_H [m^3/kg DA]: is the volume occupied by 1 kg DA (dry air) plus the water vapor that accompanies it.

What will be volume of 150 kg of humid air at 30 °C and hr = 30 %?

$$V = \frac{150 \text{ kg humid air}}{} \left| \frac{1.00 \text{ kg DA}}{1.008 \text{ kg humid air}} \right| \frac{0.87 \text{ m}^3}{\text{kg DA}} = 129 \text{ m}^3$$

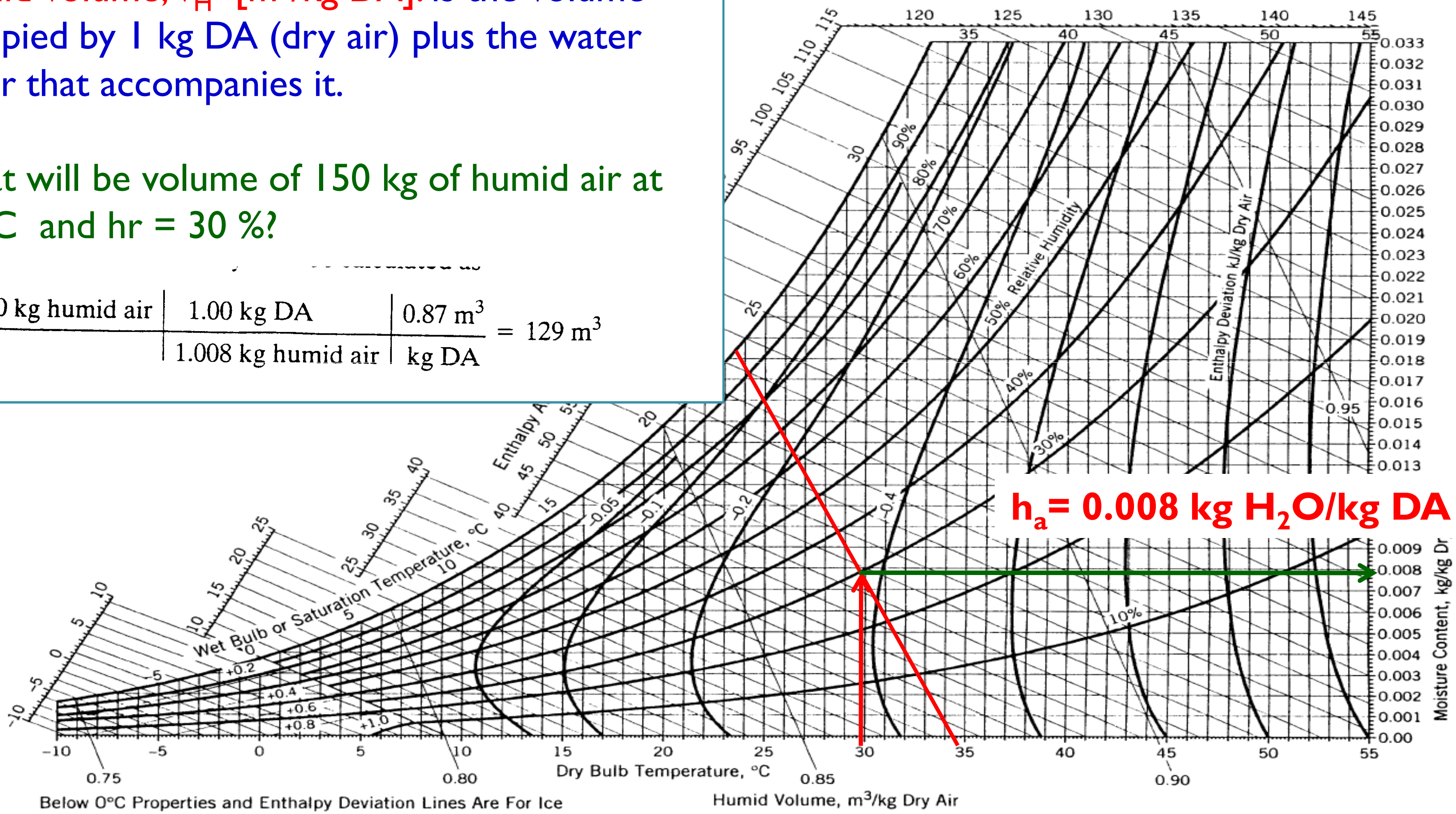

Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), ... rmission of Carrier Corporation.)

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Psychrometric Chart or Humidity Chart

Wet-bulb temperature, T_{wb}: The humid air conditions that correspond to a given wet-bulb temperature fall on a straight line on the Psychrometric chart, called a constant wet-bulb temperature line.

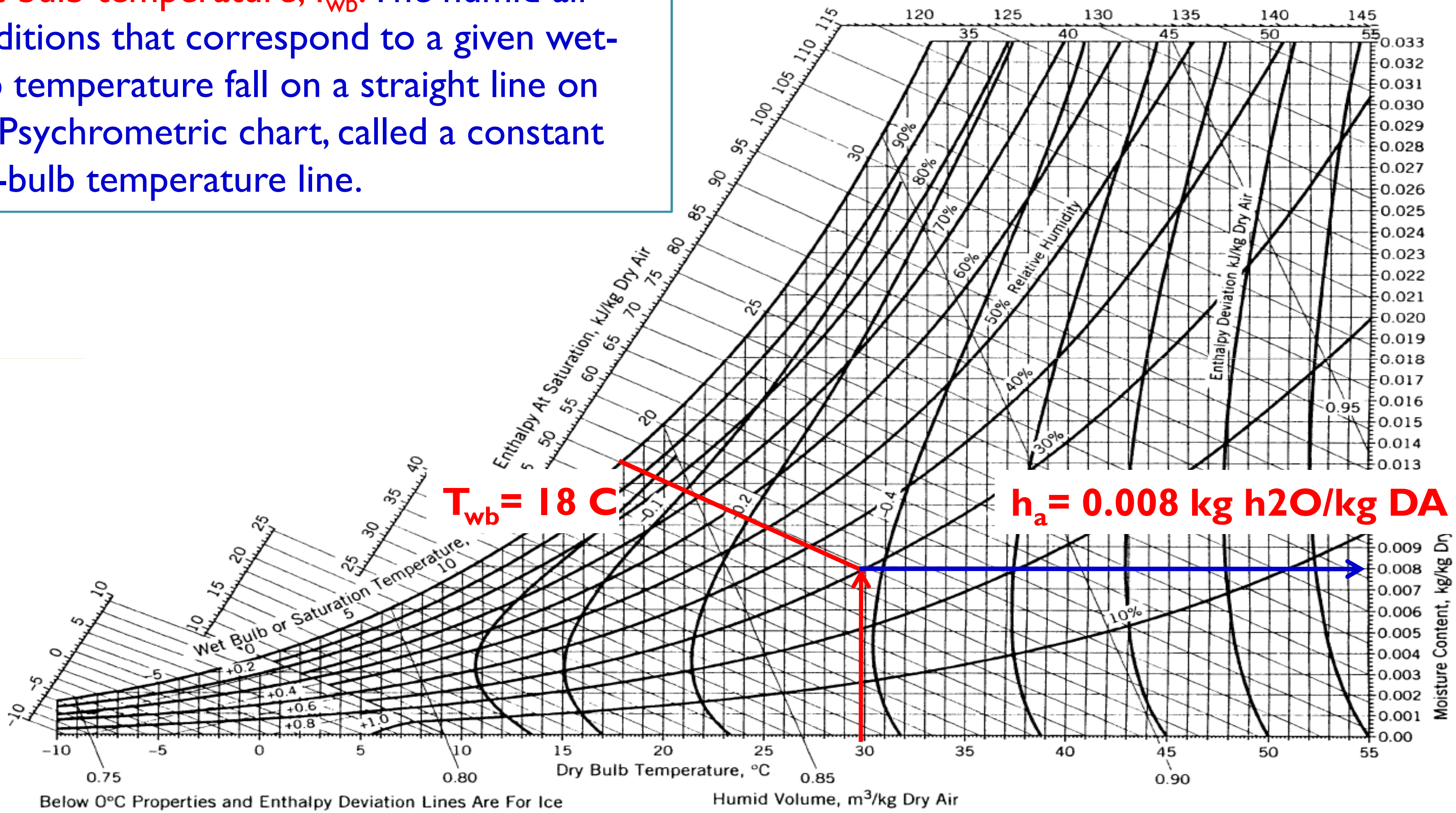


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Psychrometric Chart or Humidity Chart

Specific enthalpy of saturated air: The diagonal scale above the saturation curve on the psychrometric chart shows the enthalpy of a unit mass (1 kg or 1 lbm) of dry air plus the water vapor it contains at saturation.

Reference (H_2O (l) at 1 atm 0 °C)

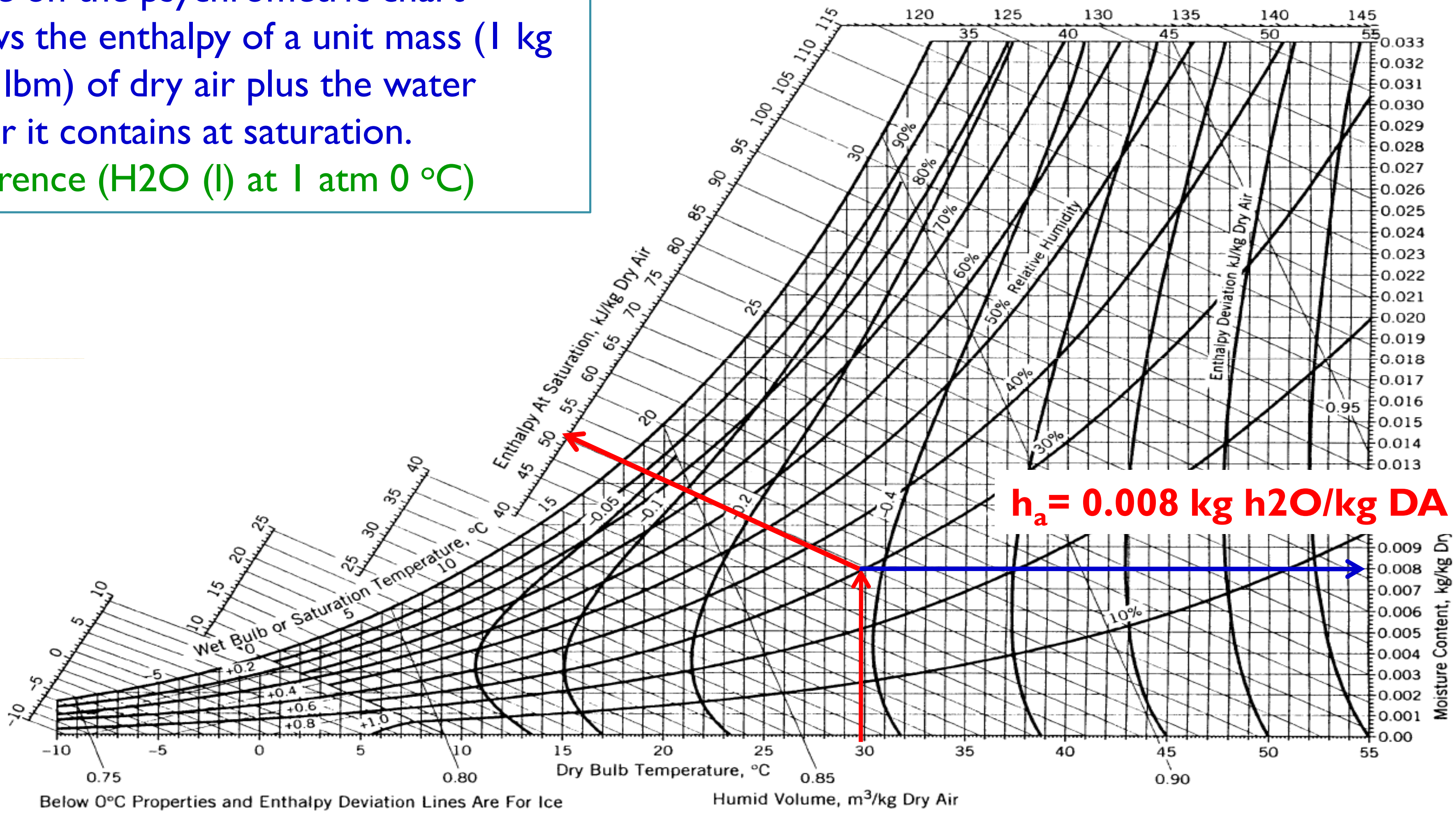


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Psychrometric Chart or Humidity Chart

For example, saturated air at 25°C and 1 atm—which has an absolute humidity h_a = 0.0202 kg H_2O/kg DA—has a specific enthalpy of 76.5 kJ/kg DA. (Verify these values of both h_a and $\hat{H}$ on Figure 8.4-1.) The enthalpy is the sum of the enthalpy changes for 1.00 kg dry air and 0.0202 kg water going from their reference conditions to 25°C. The computation shown below uses heat capacity data from Table B.2 for air and data from the steam tables (Table B.5) for water.

$$1.00\text{ kg DA}(0^\circ\text{C}) \rightarrow 1\text{ kg DA}(25^\circ\text{C})$$

$$\Downarrow$$

$$\Delta H_{\text{air}} = (1.00\text{ kg DA})\left(\frac{1\text{ kmol}}{29.0\text{ kg}}\right)\left[\int_0^{25} C_{p,\text{air}}(T)\,dT\right]\left(\frac{\text{kJ}}{\text{kmol}}\right) = 25.1\text{ kJ}$$

$$0.0202\text{ kg H}_2\text{O}(\text{l}, 0^\circ\text{C}) \rightarrow 0.0202\text{ kg H}_2\text{O}(\text{v}, 25^\circ\text{C})$$

$$\Downarrow$$

$$\Delta H_{\text{water}} = (0.0202\text{ kg})[\hat{H}_{\text{H}_2\text{O(v,25}^\circ\text{C)}} - \hat{H}_{\text{H}_2\text{O(l,0}^\circ\text{C)}}]\left(\frac{\text{kJ}}{\text{kg}}\right) = 51.4\text{ kJ}$$

$$\hat{H} = \frac{(\Delta H_{\text{air}} + \Delta H_{\text{water}})(\text{kJ})}{1.00\text{ kg DA}} = \frac{(25.1 + 51.4)\text{ kJ}}{1.00\text{ kg DA}} = 76.5\text{ kJ/kg DA}$$

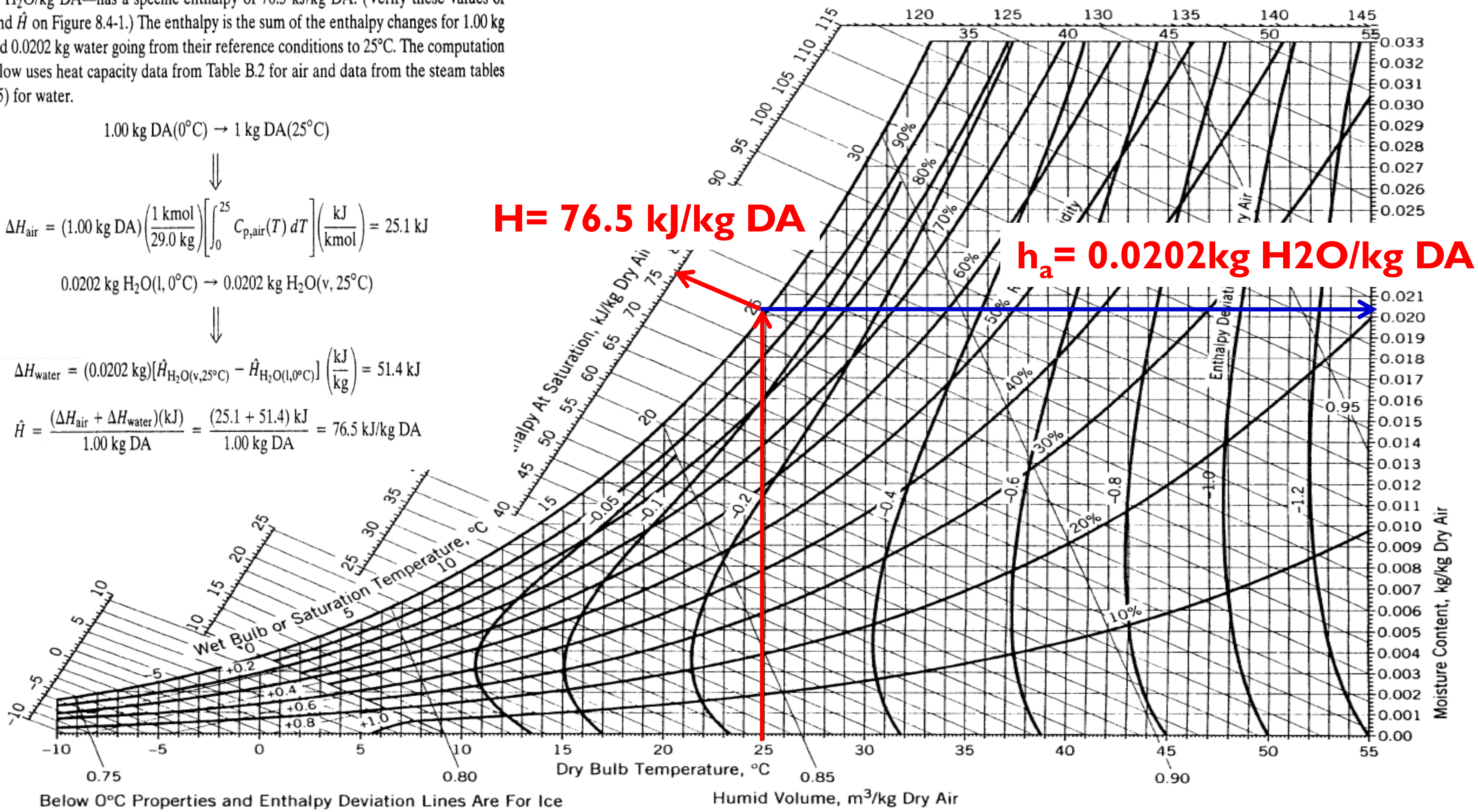


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Psychrometric Chart or Humidity Chart

- ***Enthalpy deviation***

The remaining curves on the psychrometric chart are almost vertical and convex to the left, with labeled values (on Figure 8.4-1) of −0.05, −0.1, −0.2, and so on. (The units of these numbers are kJ/kg DA). These curves are used to determine the enthalpy of humid air that is not saturated. The procedure is as follows: (a) locate the point on the chart corresponding to air at its specified condition; (b) interpolate to estimate the enthalpy deviation at this point;

(c) follow the constant wet-bulb temperature line to the enthalpy scale above the saturation curve, read the value on that scale, and add the enthalpy deviation to it.

For example, air at 35°C and 10% relative humidity has an enthalpy deviation of about −0.52 kJ/kg DA. The specific enthalpy of saturated air at the same wet-bulb temperature is 45.0 kJ/kg DA. (Verify both of these numbers.) The specific enthalpy of the humid air at the given condition is therefore (45.0 − 0.52) kJ/kg DA = 44.5 kJ/kg DA.

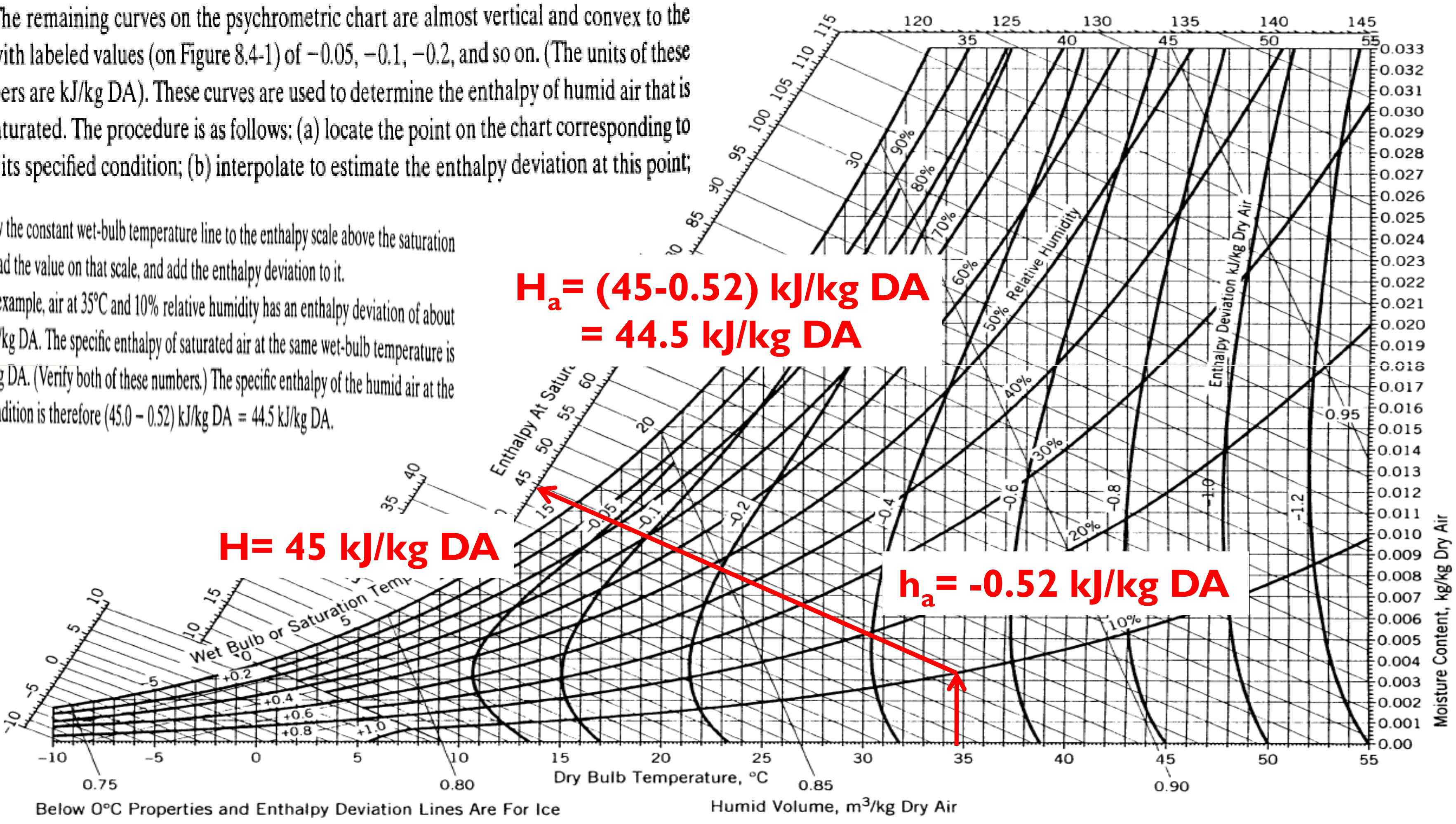
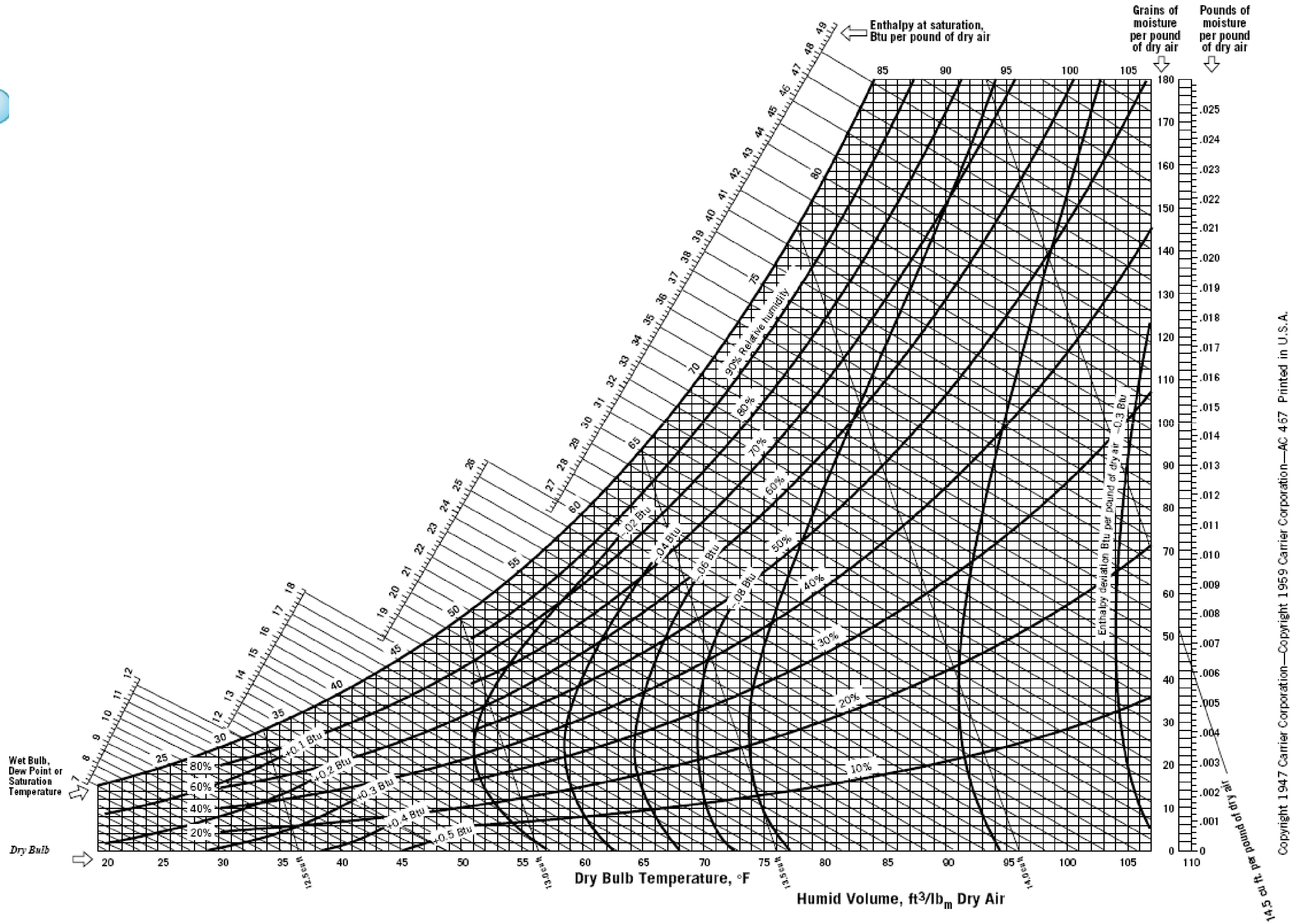


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

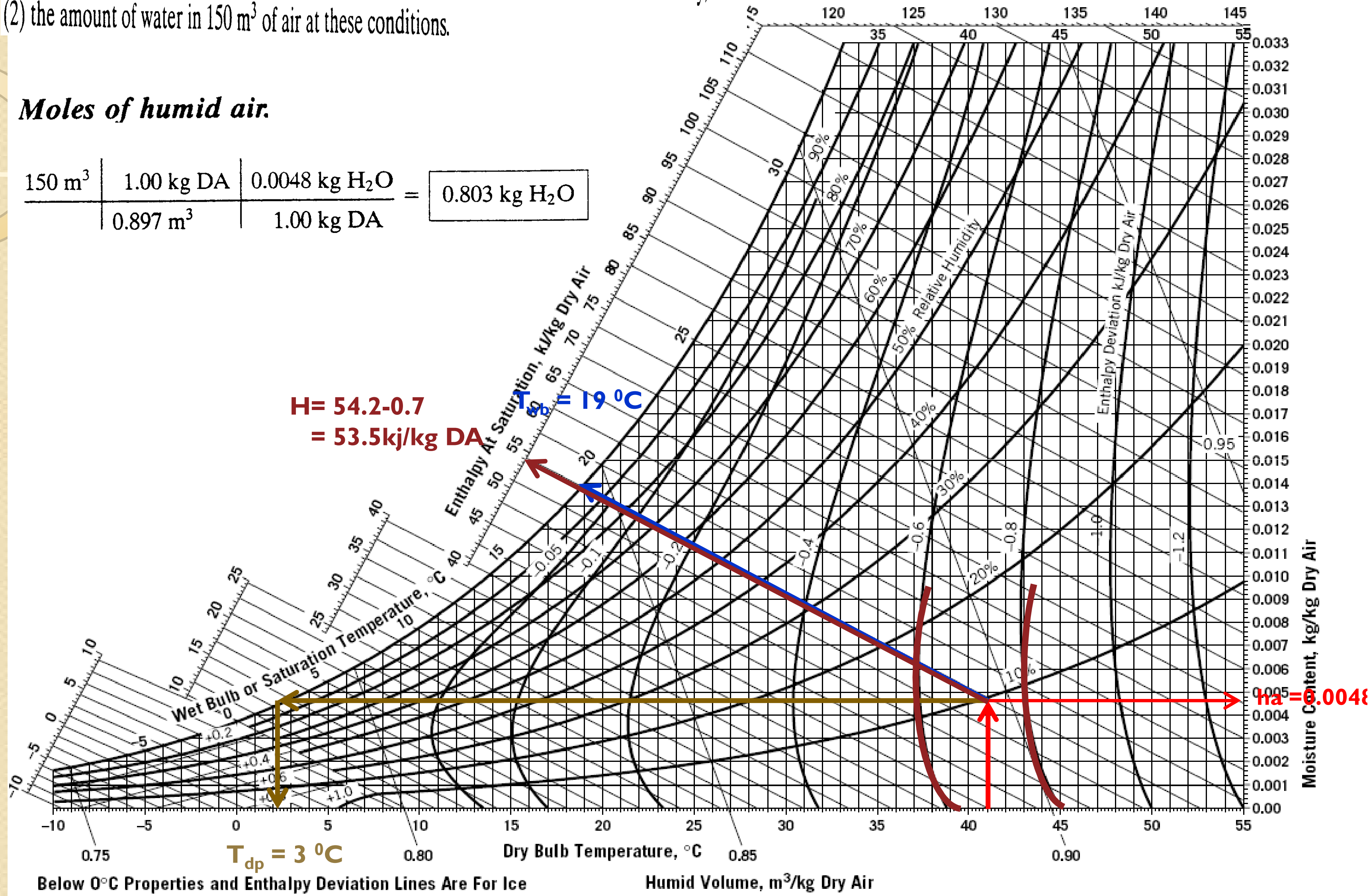
Psychometric Chart or Humidity Chart



Use the psychrometric chart to estimate (1) the absolute humidity, wet-bulb temperature, humid volume, dew point, and specific enthalpy of humid air at 41°C and 10% relative humidity, and (2) the amount of water in 150 m^3 of air at these conditions.

Moles of humid air.

$$\frac{150\ \text{m}^3}{} \left| \frac{1.00\ \text{kg DA}}{0.897\ \text{m}^3} \right| \frac{0.0048\ \text{kg H}_2\text{O}}{1.00\ \text{kg DA}} = \boxed{0.803\ \text{kg H}_2\text{O}}$$

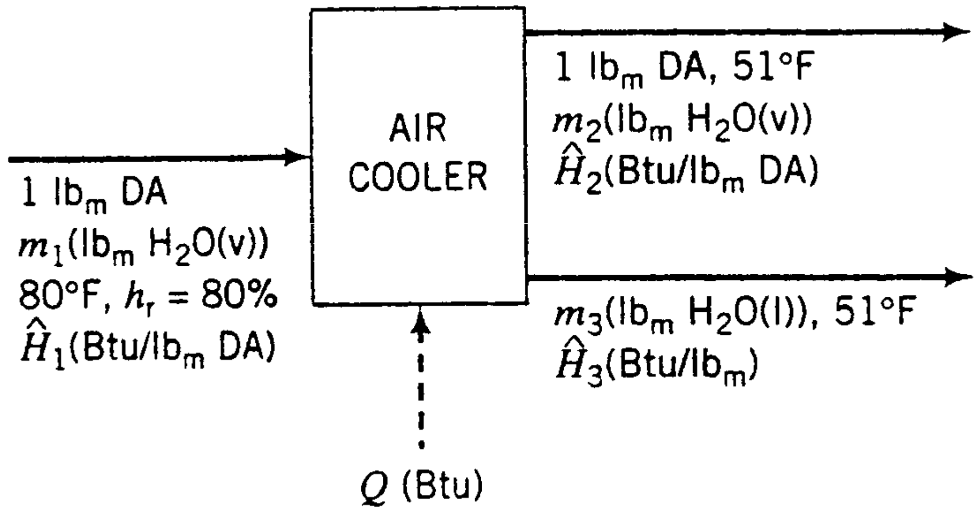


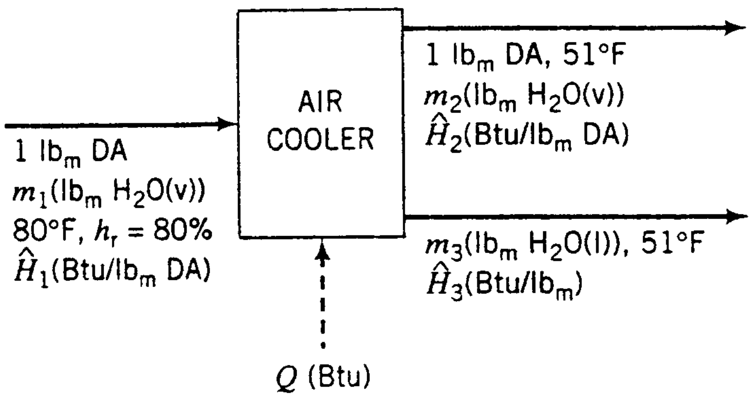
Example 8.4.6

Material and Energy Balances on an Air Conditioner

Air at 80°F and 80% relative humidity is cooled to 51°F at a constant pressure of 1 atm. Use the psychrometric chart to calculate the fraction of the water that condenses and the rate at which heat must be removed to deliver 1000 ft^3/min of humid air at the final condition.

Basis: 1 lb_m Dry Air





Point 1

$$\left.\begin{array}{r}80°\text{F}\\ 80\%\ \text{RH}\end{array}\right\}\xrightarrow{\text{Figure 8.4-2}}\begin{array}{l}h_a = 0.018\ \text{lb}_m\ \text{H}_2\text{O}/\text{lb}_m\ \text{DA}\\ \hat{H}_1 = 38.8\ \text{Btu}/\text{lb}_m\ \text{DA}\end{array}$$

$$m_1 = \frac{1.0\ \text{lb}_m\ \text{DA}}{}\left|\frac{0.018\ \text{lb}_m\ \text{H}_2\text{O}}{\text{lb}_m\ \text{DA}}\right. = 0.018\ \text{lb}_m\ \text{H}_2\text{O}$$

Point 2

$$\left.\begin{array}{r}51°\text{F}\\ \text{Saturated}\end{array}\right\}\xrightarrow{\text{Figure 8.4-2}}\begin{array}{l}h_a = 0.0079\ \text{lb}_m\ \text{H}_2\text{O}/\text{lb}_m\ \text{DA}\\ \hat{H}_2 = 20.9\ \text{Btu}/\text{lb}_m\ \text{DA}\end{array}$$

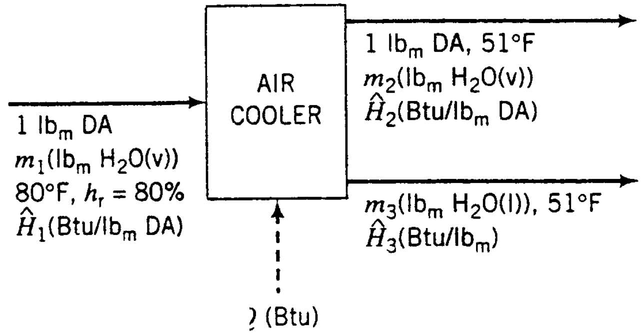
$$m_2 = \frac{1.0\ \text{lb}_m\ \text{DA}}{}\left|\frac{0.0079\ \text{lb}_m\ \text{H}_2\text{O}}{\text{lb}_m\ \text{DA}}\right. = 0.0079\ \text{lb}_m\ \text{H}_2\text{O}$$

Balance on H_2O

$$m_1 = m_2 + m_3$$

$$\Big\Downarrow \begin{array}{l} m_1 = 0.018\ \text{lb}_m\\ m_2 = 0.0079\ \text{lb}_m\end{array}$$

$$m_3 = 0.010\ \text{lb}_m\ \text{H}_2\text{O condensed}$$



Fraction H_2O Condensed

$$\frac{0.010\ \text{lb}_m\ \text{condensed}}{0.018\ \text{lb}_m\ \text{fed}} = \boxed{0.555}$$

Enthalpy of Condensate

Since the reference condition for water on Figure 8.4-2 is liquid water at 32°F, we must use the same condition to calculate $\hat{H}_3$.

$$H_2O(l, 32°F) \longrightarrow H_2O(l, 51°F)$$

$$\Delta\hat{H} = \hat{H}_3 = 1.0\ \frac{\text{Btu}}{\text{lb}_m \cdot °F}(51°F - 32°F) = 19.0\ \text{Btu/lb}_m\ H_2O$$

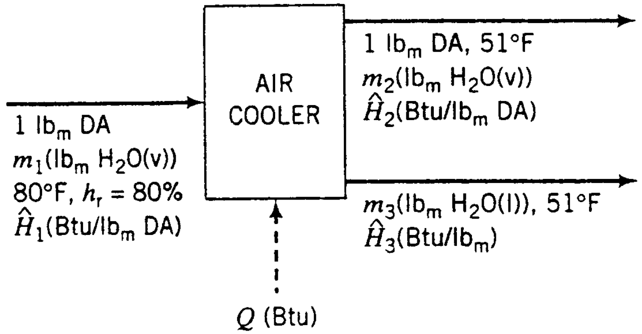
Energy Balance

The open-system energy balance with W_s, ΔE_k, and ΔE_p set equal to zero is

$$Q = \Delta H = \sum_{\text{out}} m_i\hat{H}_i - \sum_{\text{in}} m_i\hat{H}_i$$

References: **Dry air (DA) (g, 0°F, 1 atm), H_2O (l, 32°F, 1 atm)**

Substance	m_{in}	$\hat{H}_{in}$	m_{out}	$\hat{H}_{out}$
Humid air	1.0 lb_m DA	38.8 Btu/lb_m DA	1.0 lb_m DA	20.9 Btu/lb_m DA
$H_2O(l)$	—	—	0.010 lb_m	19 Btu/lb_m



$$Q = \Delta H = \frac{1.0\ \text{lb}_\text{m}\ \text{DA}}{} \left| \frac{20.9\ \text{Btu}}{\text{lb}_\text{m}\ \text{DA}} \right. + \frac{0.010\ \text{lb}_\text{m}\ \text{H}_2\text{O(l)}}{} \left| \frac{19\ \text{Btu}}{\text{lb}_\text{m}\ \text{H}_2\text{O}} \right. - \frac{1.0\ \text{lb}_\text{m}\ \text{DA}}{} \left| \frac{38.8\ \text{Btu}}{\text{lb}_\text{m}\ \text{DA}} \right.$$

$$= -17.7\ \text{Btu}$$

Scale up $(1000\ \text{ft}^3/\text{min})/(\dot{V}_\text{basis})$

$$\hat{V}_\text{H} = 13.0\ \text{ft}^3/\text{lb}_\text{m}\ \text{DA}$$

$$\Downarrow$$

$$V_\text{basis} = \frac{1.0\ \text{lb}_\text{m}\ \text{DA}}{} \left| \frac{13.0\ \text{ft}^3}{\text{lb}_\text{m}\ \text{DA}} \right. = 13.0\ \text{ft}^3$$

$$\Downarrow$$

$$\dot{Q} = \frac{-17.7\ \text{Btu}}{} \left| \frac{1000\ \text{ft}^3/\text{min}}{13.0\ \text{ft}^3} \right. = \boxed{-1360\ \text{Btu/min}}$$