Chapter 8
Balances on Nonreactive Processes

PSYCHROMETRIC CHART

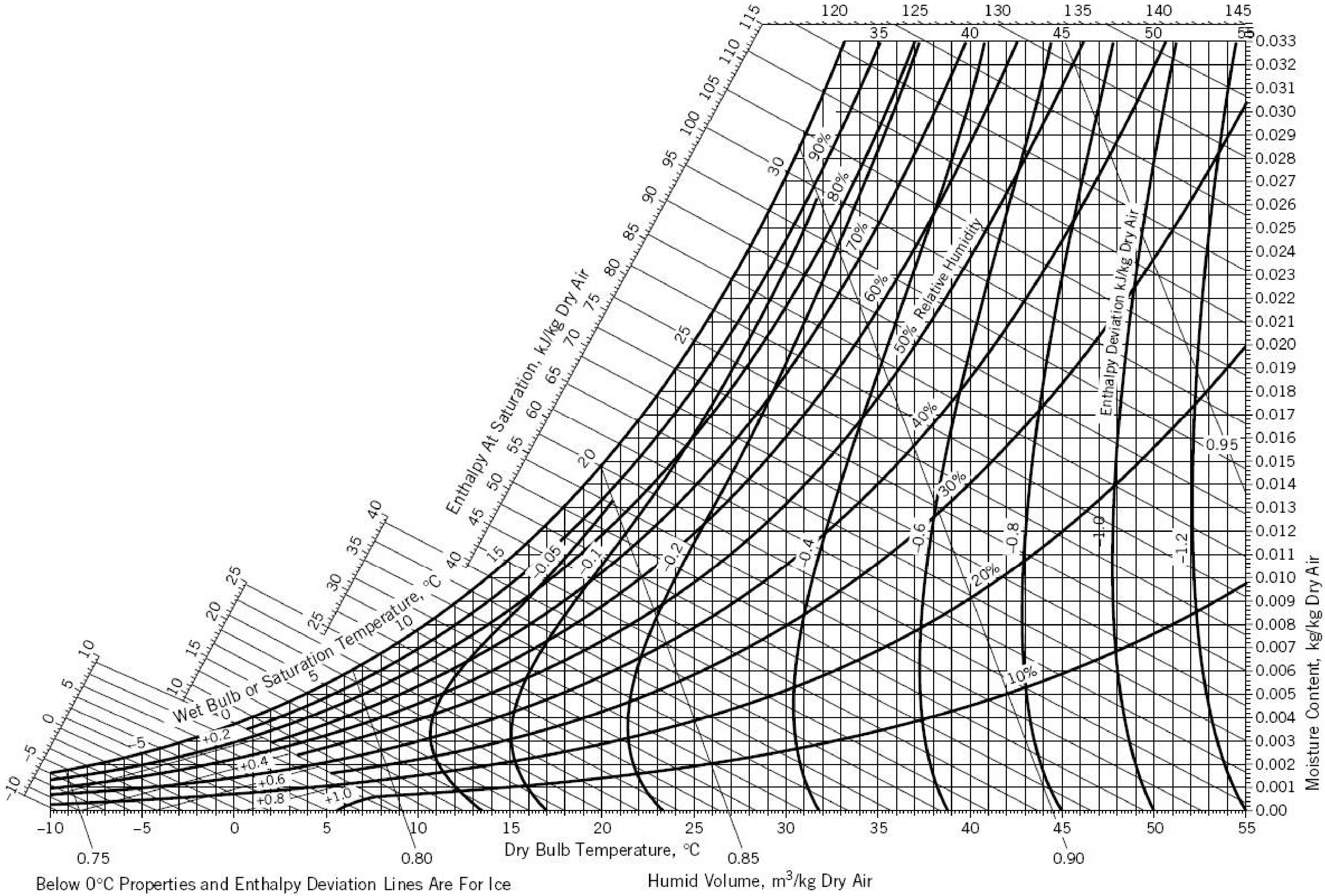


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Figure 8.4-1 (p. 385)

Terminologies

- Absolute Humidity
- % Relative Humidity
- Dew Point
- Humid Volume
- Dry-bulb Temperature
- Wet-bulb Temperature
- Specific Enthalpy of Saturated Air (Enthalpy Deviation to be considered)

- ***Absolute Humidity*** **refers to the moisture content of air**

$$h_a = \frac{\text{kg water (vapor)}}{\text{kg DA}}$$

- ***Relative Humidity*** **Ratio of partial pressure to vapor of liquid at gas temperature and pressure**

$$h_r = \frac{p_{H_2O}}{p^*_{H_2O}(T)} \times 100$$

% RH = f (T, P)

Dew Point Temperature

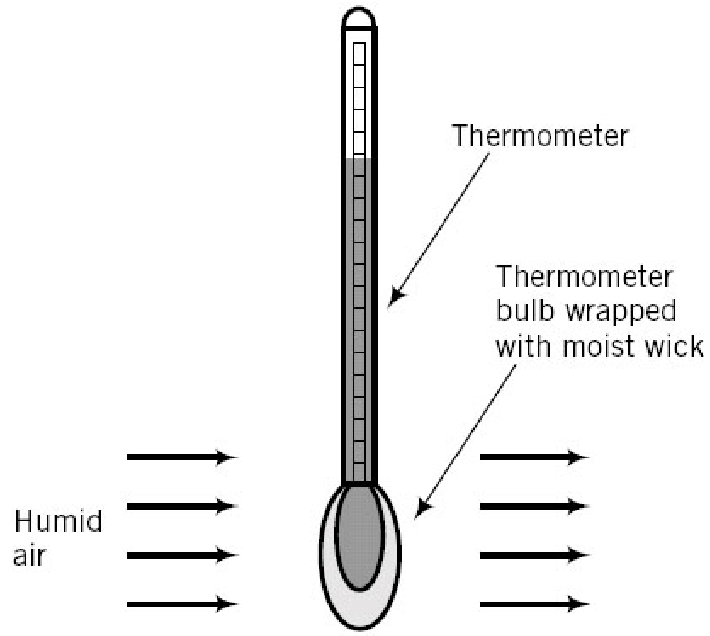
- Temperature at which
  - water vapor starts to condense out of the air
  - air becomes completely saturated
  - humid air becomes saturated if it is cooled at constant temperature
  - first liquid droplet forms

Dry Bulb Temperature

- The Dry Bulb Temperature refers basically to the ambient air temperature
- It is called "Dry Bulb" because the air temperature is indicated by a thermometer not affected by the moisture of the air
- Dry-bulb temperature can be measured using a normal thermometer freely exposed to the air but shielded from radiation and moisture

Wet Bulb Temperature

- Function of temperature and humidity
- Hygrometers are instruments comprising both wet-bulb and dry-bulb thermometers
- Temperature shown when environment just adjacent to bulb is just saturated



Hygrometer

[***Hygrometer by masons***]

- Humid Volume - Volume occupied by (1 Kg DA + ha kg water vapor that accompanies it)
- Specific Enthalpy of saturated air:

  Reference state: liquid water and air both at 0 ^{o}C and 1 atm.
- Enthalpy deviation: For enthalpy of non-saturated air, enthalpy deviation must be added to the enthalpy of saturated air.

Psychrometric chart

- plot of several properties of a gas-vapor mixture
  - Air – Water system at 1 atm : Figure 8.4-1
- DOF
  - F = C – P + 2 = 2 –1 + 2 = 3
  - P : 1 atm for pychrometric chart
  - Other 2 varibles :
    - T_{db} and T_{wb}
    - T_{db} or h_r , ...
- How to read psychrometric chart ?
  - 2 varibles needed to locate a point in the chart :
    - T_{db} and T_{wb}
    - T_{db} or h_r , ...
  - H : add enthalpy deviation to the H at saturation
- See example 8.4-5 for reading the psychrometric chart

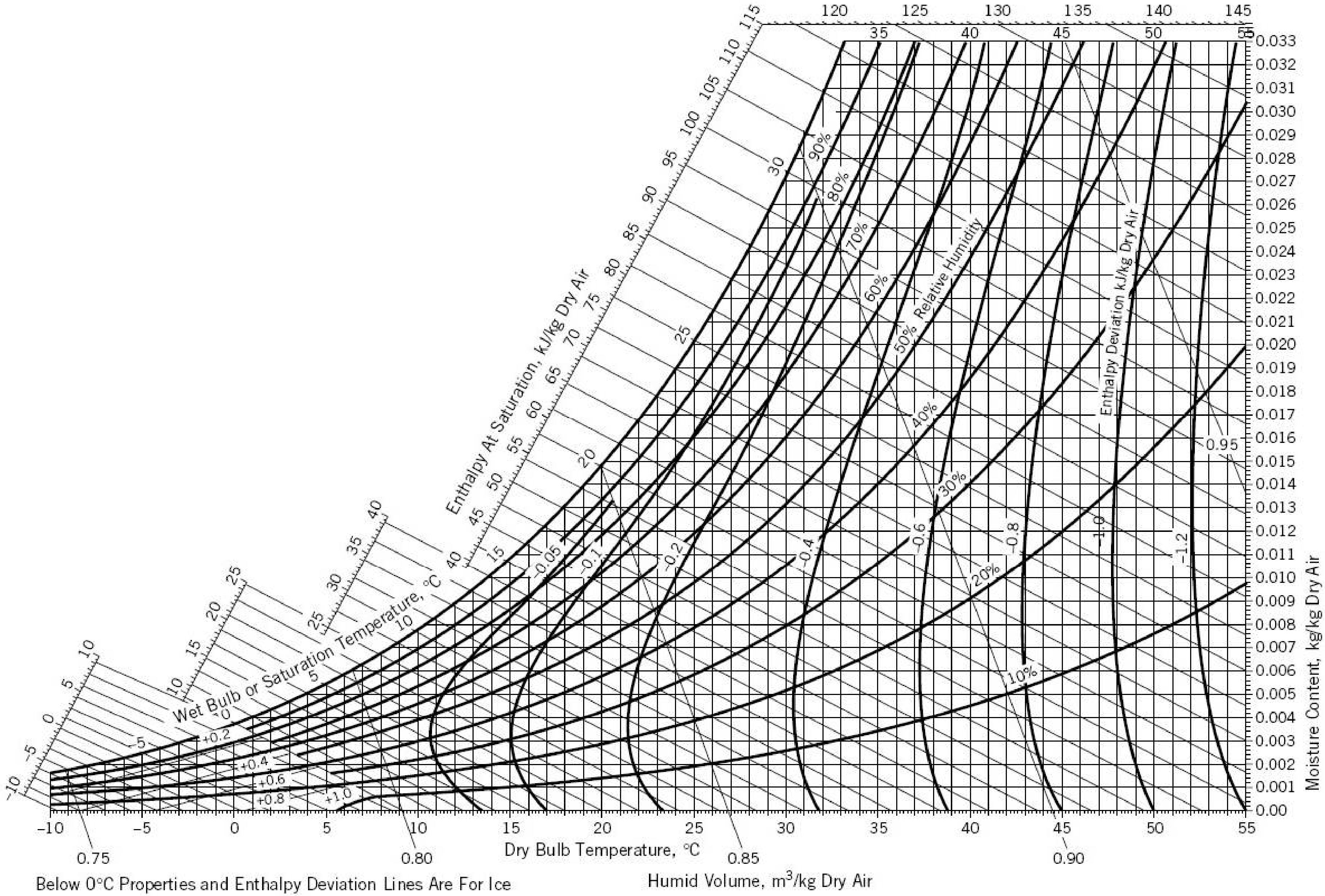
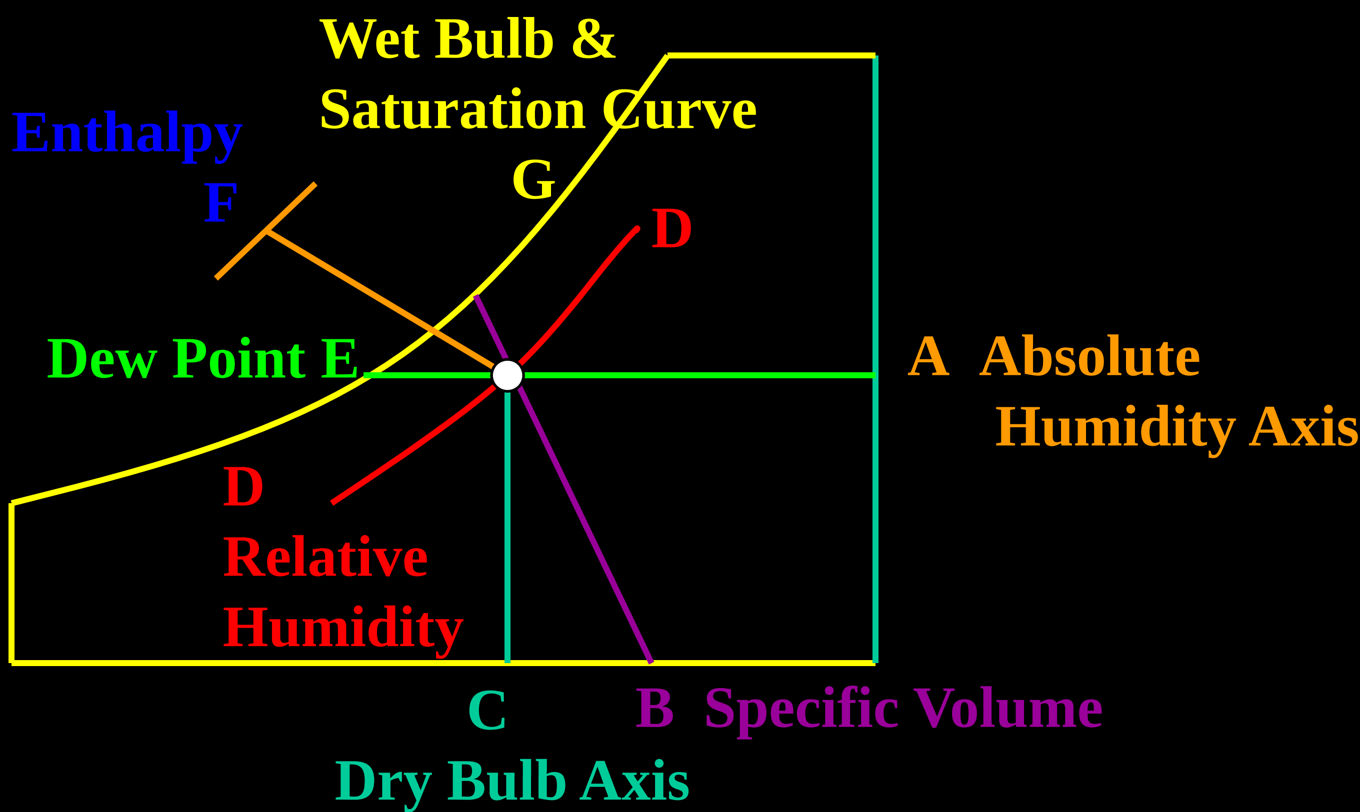


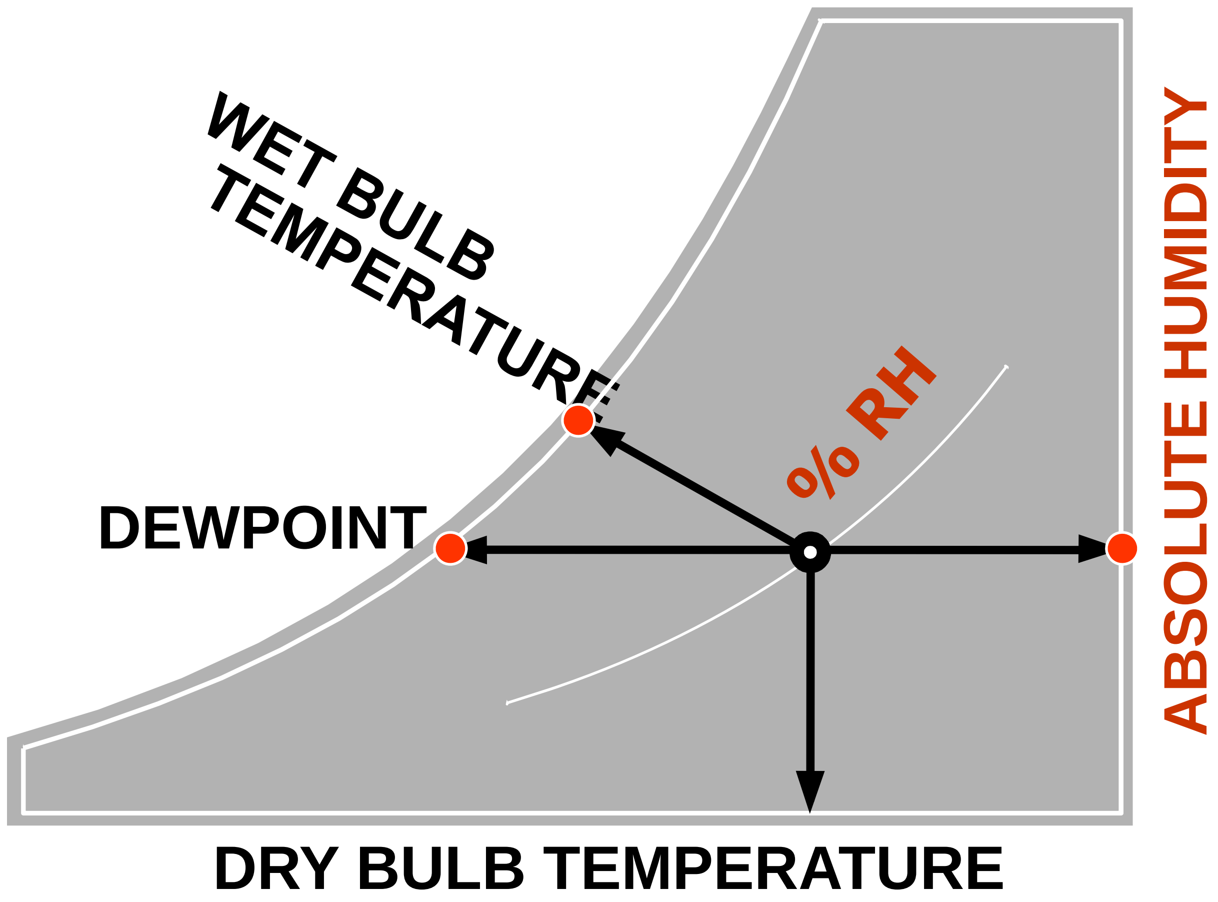
Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Figure 8.4-1 (p. 385)

Psychrometric Chart



Psychrometric Chart / Humidity Chart



Ref. state

H_2O (L, 0^0C, 1 atm)

Dry Air (0^0C, 1 atm)

F =??

Example 8.4-5

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.

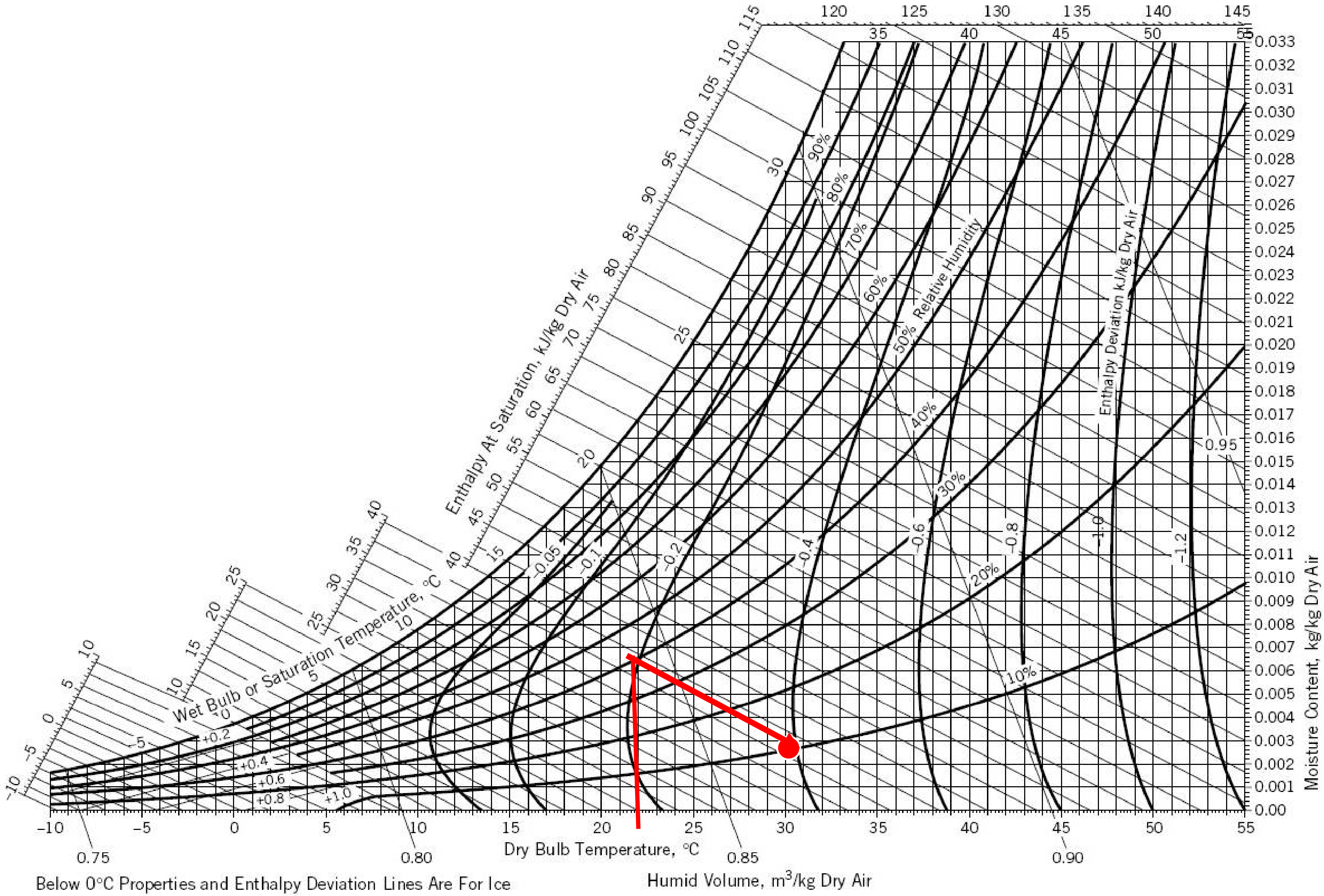
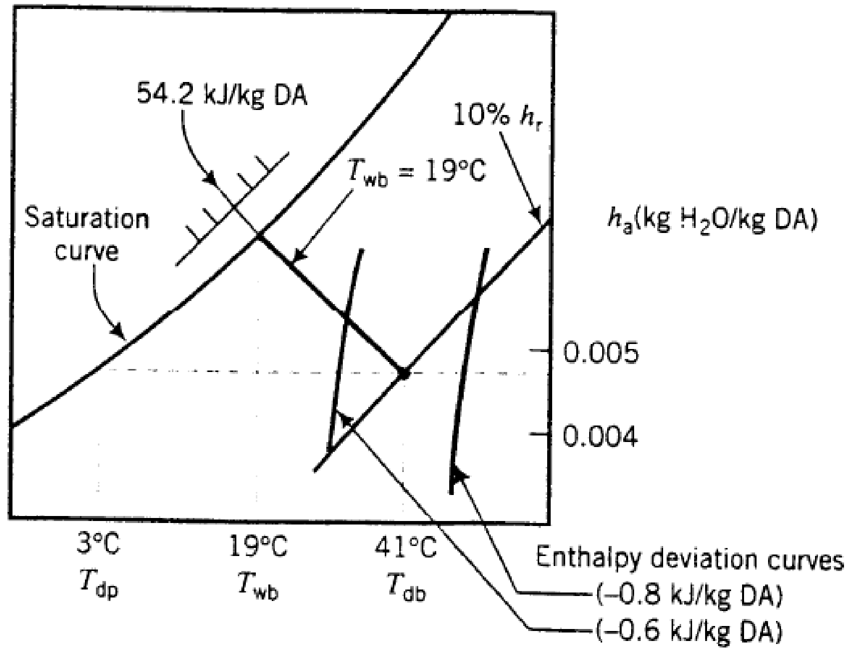


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

Figure 8.4-1 (p. 385)

Following is a sketch of the psychrometric chart (Figure 8.4-1) showing the given state of the air:



1. Reading from the chart,

$$h_a \approx 0.0048 \text{ kg } H_2O/\text{kg DA}$$
$$T_{wb} = 19°C$$
$$\hat{V}(m^3/\text{kg DA}) \approx 0.897 \text{ (curve not shown)}$$

The dew point is the temperature at which the air with the given water content would be saturated at the same total pressure (1 atm) and is therefore located at the intersection of the horizontal constant absolute humidity line ($h_a \equiv 0.0048$) and the saturation curve, or

$$T_{dp} = 3°C$$

The specific enthalpy of saturated air at $T_{wb} = 19°C$ is 54.2 kJ/kg DA. Since the point corresponding to 41°C and 10% relative humidity falls roughly midway between the enthalpy deviation curves corresponding to −0.6 kJ/kg and −0.8 kJ/kg, we may calculate $\hat{H}$ as

$$\hat{H} = (54.2 - 0.7) \text{ kJ/kg DA}$$

$$\Downarrow$$

$$\boxed{\hat{H} = 53.5 \text{ kJ/kg DA}}$$

2. ***Moles of humid air.*** From Figure 8.4-1, the humid volume of the air is 0.897 m^3/kg DA. We therefore calculate

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

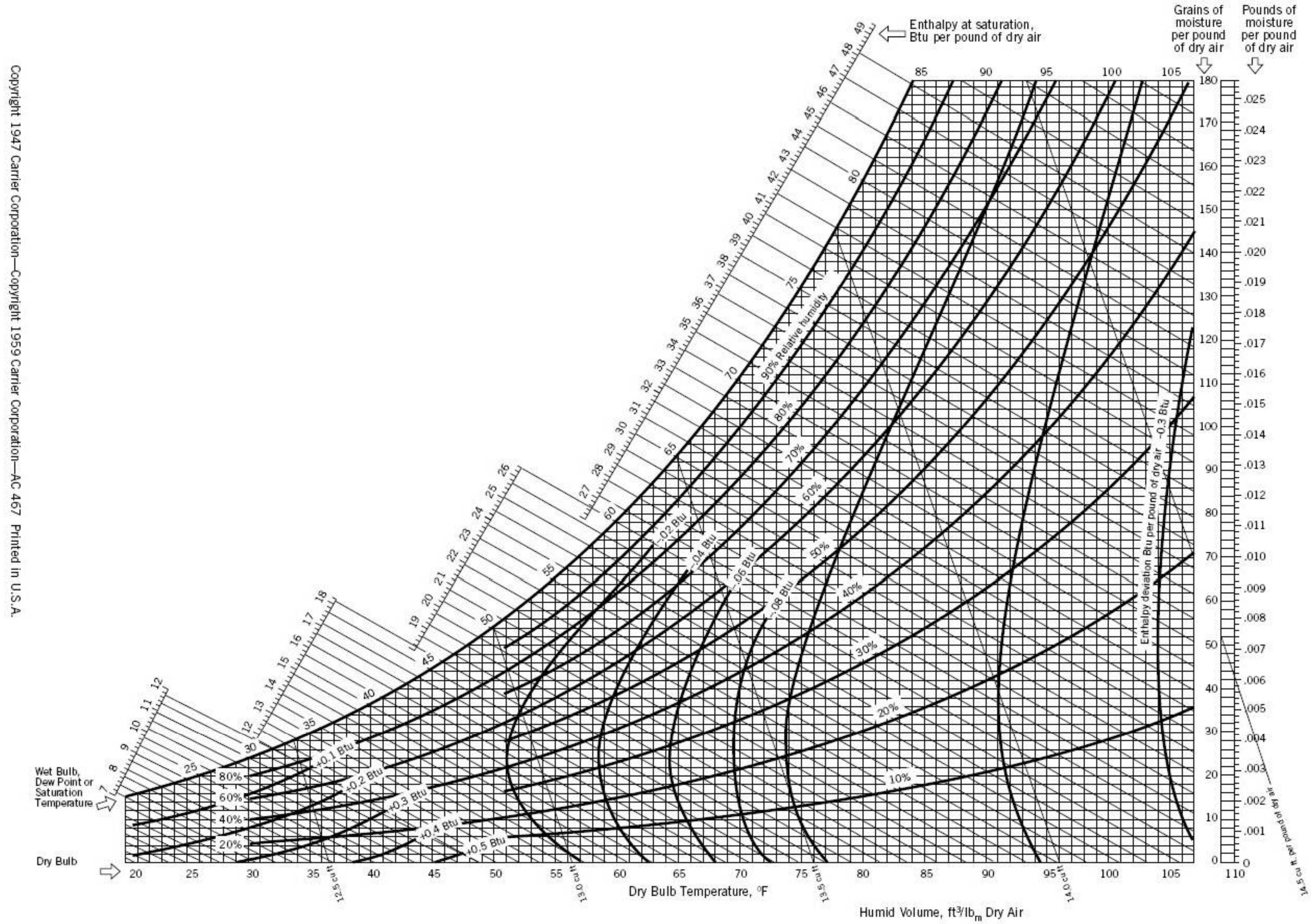
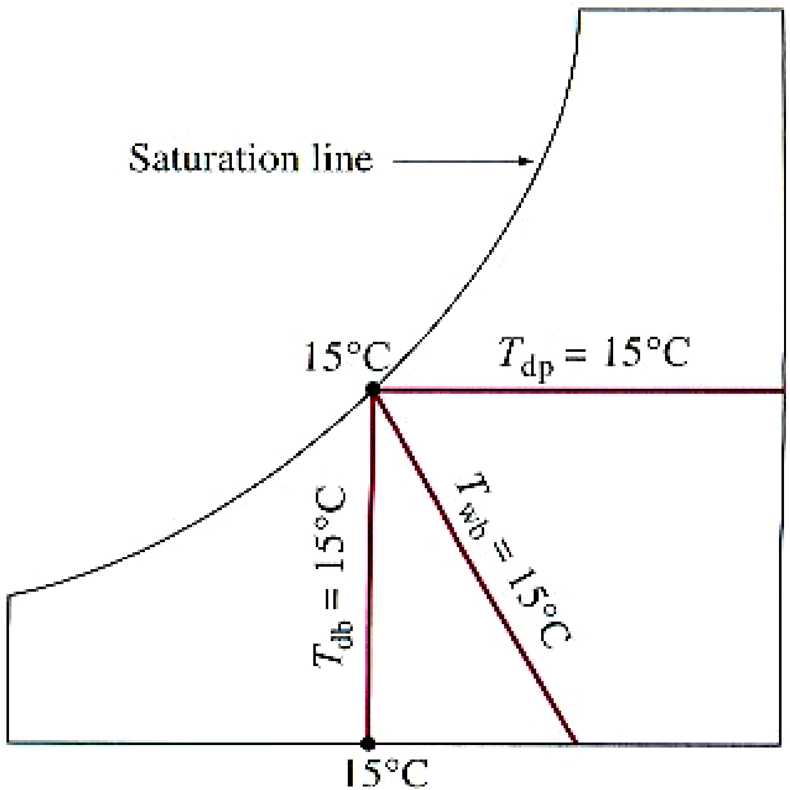


Figure 8.4-2 Psychrometric chart—American Engineering units. Reference states: H_2O (L, 32°F, 1 atm), dry air (0°F, 1 atm). (Reprinted with permission of Carrier Corporation.)

Figure 8.4-2 (p. 386)

- For a saturated air, the dry – bulb, wet – bulb and dew – point temperature are identical.



CT – 3

Tuesday (10/7/2012) at 1 pm

Syllabus: Chapter 8

Open Book

8.4e Adiabatic Humidification

- Adiabatic humidification
  - evaporation of a liquid into gas-liquid mixture
  - latent heat required to evaporate liquid is provided by the sensible heat lost by the gas phase.
  - drying of solid product
  - production of humid air
- For air-water system, adiabatic saturation curve coincide with the constant wet-bulb temperature line.

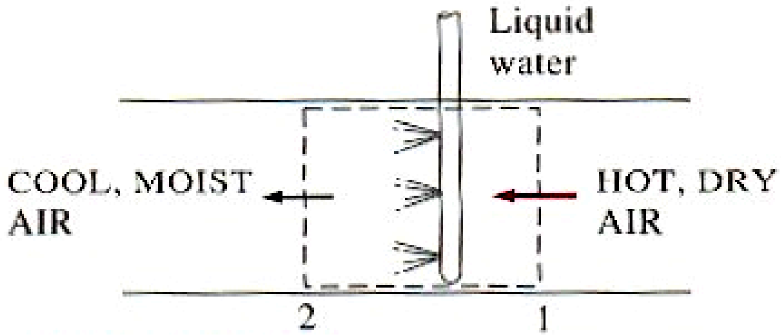
Adiabatic Cooling

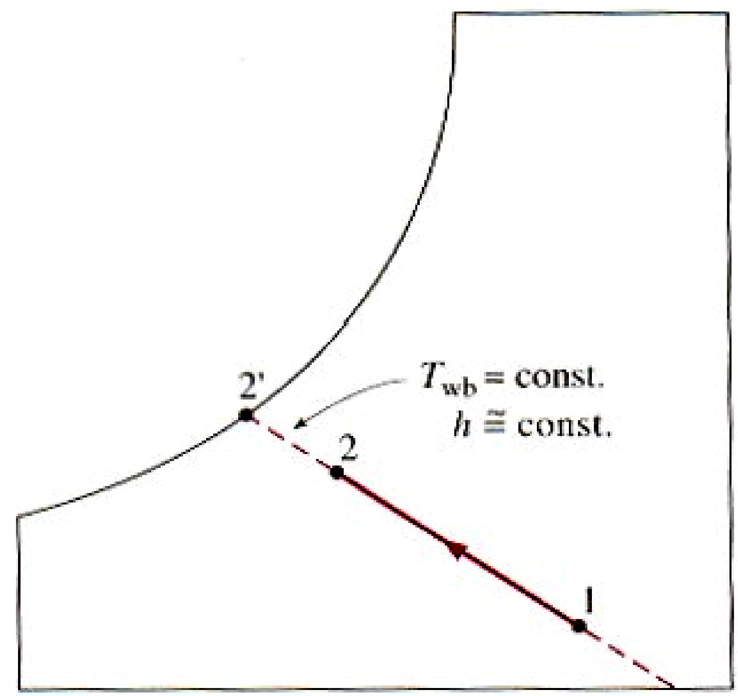
- Spray cooling, spray humidification
- Spray dehumidification
- Drying
- Spray drying

} visit Unit Operation Lab

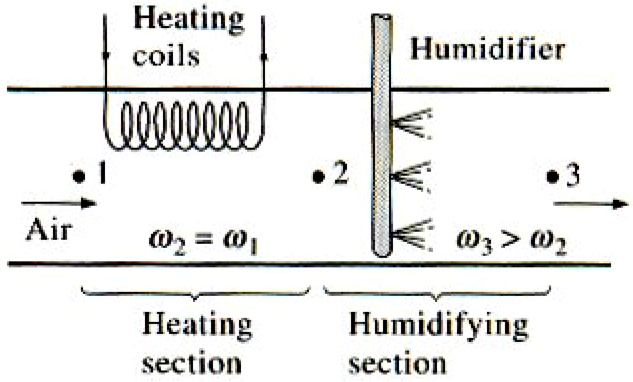
Example 8.4-7: adiabatic humidification

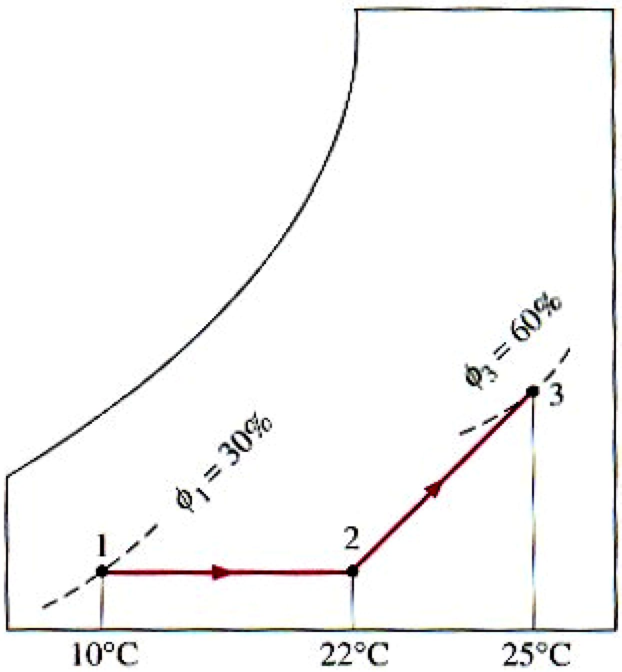
- During evaporative cooling the wet bulb temperature remains constant.
- Cooling with humidification



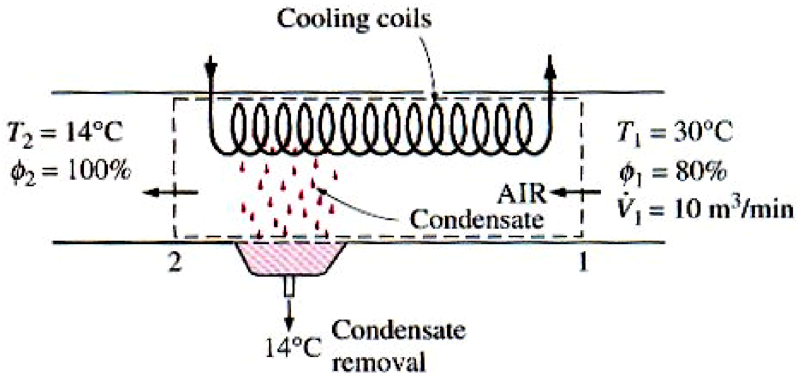


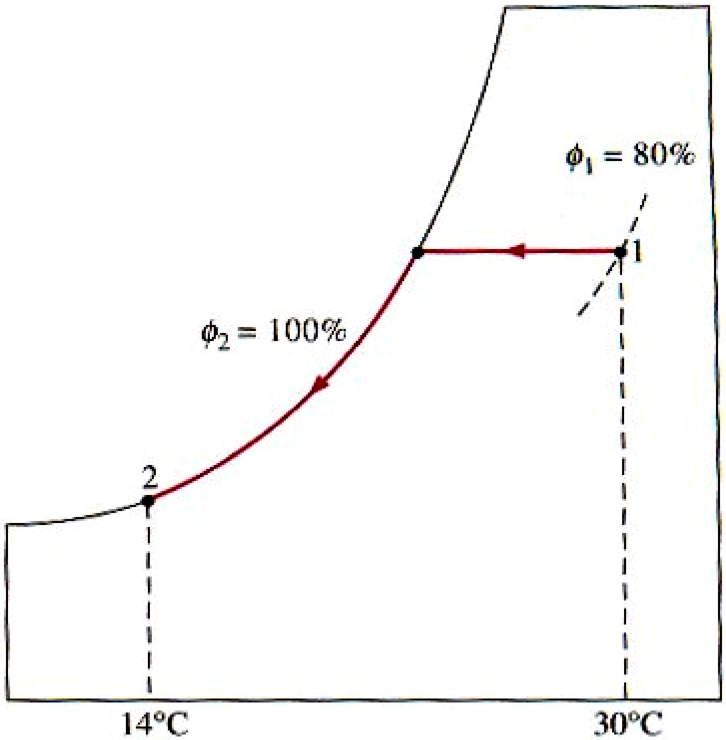
Heating with Humidification





Cooling with Dehumidification





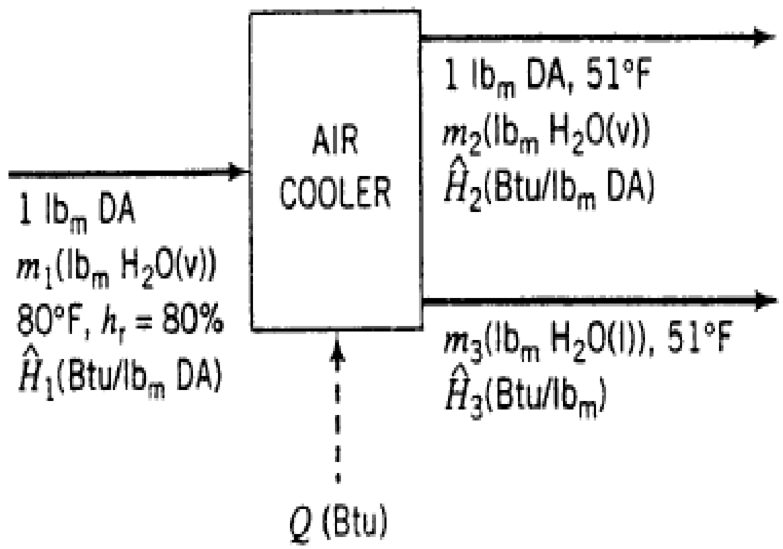
Example 8.4-6

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[12]

A flowchart for the process is shown below. By convention we show heat transfer (Q) into the process unit, but since the air is being cooled we know that Q will be negative.



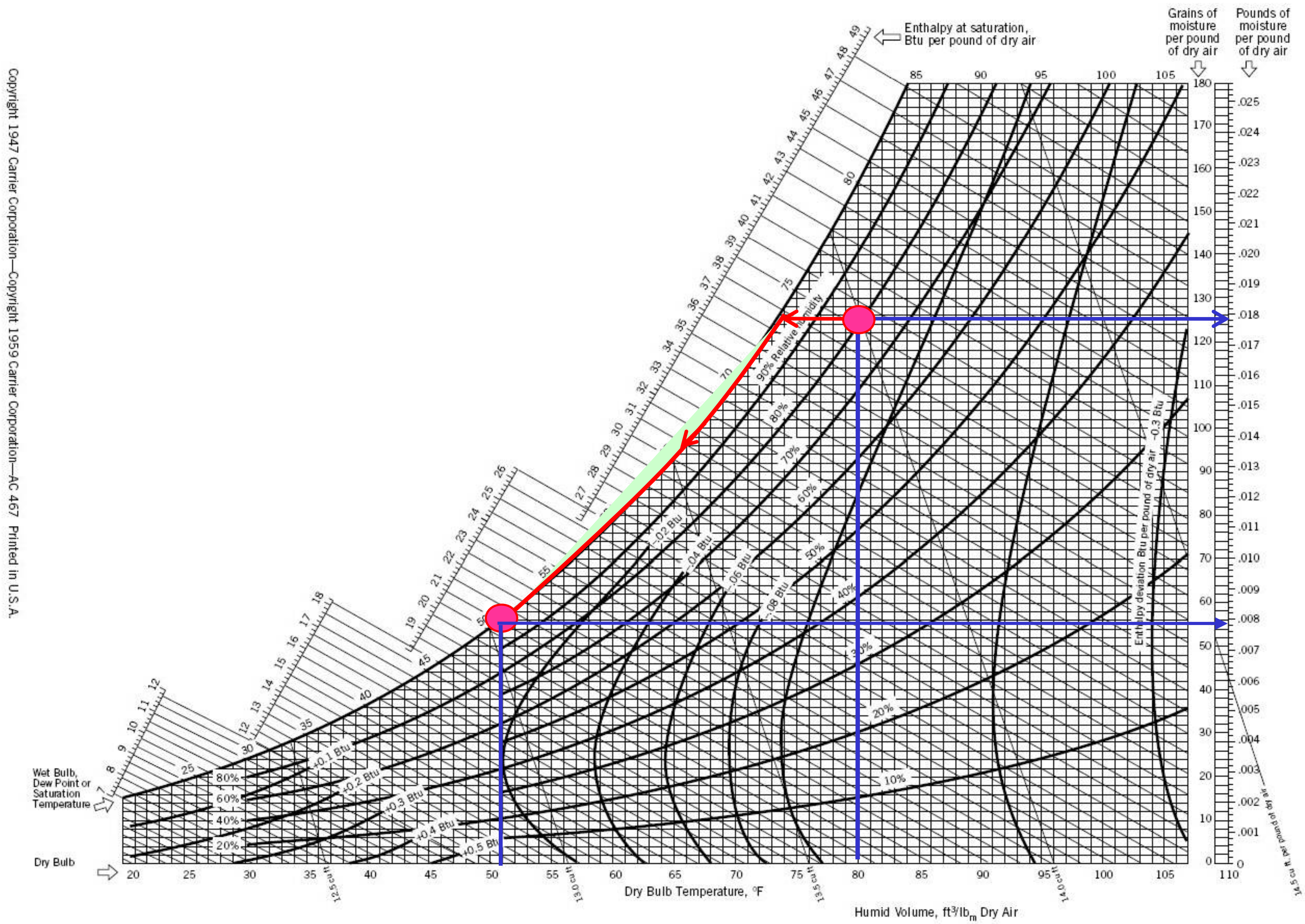


Figure 8.4-2 Psychrometric chart—American Engineering units. Reference states: H_2O (L, 32°F, 1 atm), dry air (0°F, 1 atm). (Reprinted with permission of Carrier Corporation.)

Figure 8.4-2 (p. 386)

Point 1

$$\left.\begin{array}{r}80°F \\ 80\%\ RH\end{array}\right\} \xrightarrow{\text{Figure 8.4-2}} \begin{array}{l} h_a = 0.018\ lb_m\ H_2O/lb_m\ DA \\ \hat{H}_1 = 38.8\ Btu/lb_m\ DA \end{array}$$

$$m_1 = \frac{1.0\ lb_m\ DA}{} \left| \frac{0.018\ lb_m\ H_2O}{lb_m\ DA} \right. = 0.018\ lb_m\ H_2O$$

Point 2

$$\left.\begin{array}{r}51°F \\ Saturated\end{array}\right\} \xrightarrow{\text{Figure 8.4-2}} \begin{array}{l} h_a = 0.0079\ lb_m\ H_2O/lb_m\ DA \\ \hat{H}_2 = 20.9\ Btu/lb_m\ DA \end{array}$$

$$m_2 = \frac{1.0\ lb_m\ DA}{} \left| \frac{0.0079\ lb_m\ H_2O}{lb_m\ DA} \right. = 0.0079\ lb_m\ H_2O$$

Balance on H_2O

$$m_1 = m_2 + m_3$$

$$\Big\Downarrow \begin{array}{l} m_1 = 0.018\ lb_m \\ m_2 = 0.0079\ lb_m \end{array}$$

$$m_3 = 0.010\ lb_m\ H_2O\ condensed$$

Fraction H_2O Condensed

$$\frac{0.010\ lb_m\ condensed}{0.018\ lb_m\ fed} = \boxed{0.555}$$

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 $\hat{H}_3$.

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

$$\Delta \hat{H} = \hat{H}_3 = 1.0 \frac{\text{Btu}}{\text{lb}_m \cdot °\text{F}}(51°F - 32°F) = 19.0 \text{ Btu/lb}_m \text{ H}_2\text{O}$$

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

The references were of necessity chosen to be the ones used to generate the psychrometric chart. Substituting the values in the table into the energy balance yields

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

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

To calculate the cooling requirement for 1000 ft^3/min of delivered air, we must first determine the volume of delivered air corresponding to our assumed basis and scale the calculated value of Q by the ratio $(1000\ \text{ft}^3/\text{min})/(V_{\text{basis}})$. From the psychrometric chart, for humid air saturated at 51°F

$$\hat{V}_H = 13.0\ \text{ft}^3/\text{lb}_m\ \text{DA}$$

$$\Downarrow$$

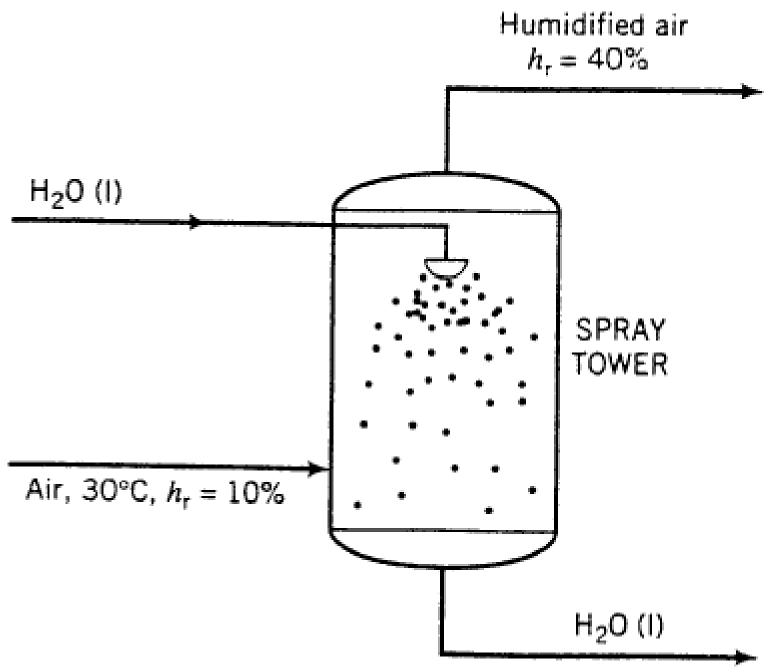
$$V_{\text{basis}} = \frac{1.0\ \text{lb}_m\ \text{DA}}{} \left| \frac{13.0\ \text{ft}^3}{\text{lb}_m\ \text{DA}} \right. = 13.0\ \text{ft}^3$$

$$\Downarrow$$

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

Adiabatic Humidification

A stream of air at 30°C and 10% relative humidity is humidified in an adiabatic spray tower operating at $P \approx 1$ atm. The emerging air is to have a relative humidity of 40%.



1. Determine the absolute humidity and the adiabatic saturation temperature of the entering air.
2. Use the psychrometric chart to calculate (i) the rate at which water must be added to humidify 1000 kg/h of the entering air, and (ii) the temperature of the exiting air.

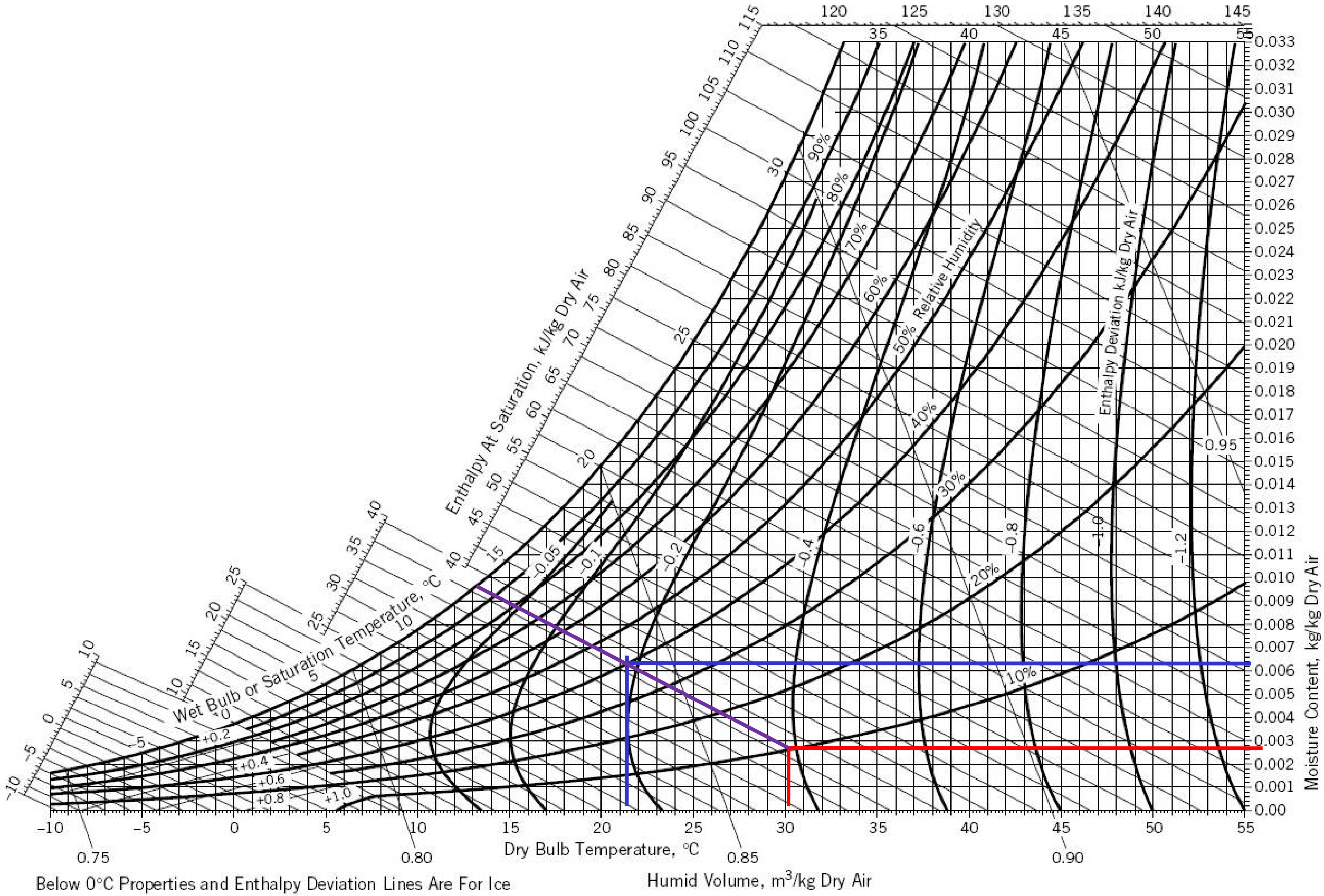


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)

1. Air at 30°C, 10% relative humidity

$\Downarrow$ Figure 8.4-1

$$h_a = 0.0026 \text{ kg H}_2\text{O/kg DA}$$

$$T_{wb} = T_{as} = 13.2°\text{C}$$

2. The state of the outlet air must lie on the $T_{wb} = 13.2°$C line. From the intersection of this line with the curve for $h_r = 40\%$, the absolute humidity of the exit gas is determined to be 0.0063 kg H_2O/kg DA. The inlet (and outlet) flow rate of dry air, $\dot{m}_{DA}$, is

$$\dot{m}_{DA} = (1000 \text{ kg air/h})(1 \text{ kg DA}/1.0026 \text{ kg air}) = 997.4 \text{ kg DA/h}$$

The amount of water that must be evaporated, $\dot{m}_{H_2O}$, may be calculated as the difference between the outlet and inlet water flow rates in the air stream.

$$\dot{m}_{H_2O} = (997.4 \text{ kg DA/h})(0.0063 - 0.0026) \frac{\text{kg H}_2\text{O}}{\text{kg DA}}$$

$$= \boxed{3.7 \text{ kg H}_2\text{O/h}}$$

From Figure 8.4-1 the temperature of the exiting air is $\boxed{21.2°\text{C}}$.

Class Test - 3

A continuous rotary dryer is used to dry wet wood chips. The dryer operates at 1 atm pressure. The wet chips containing 42 wt% water enter the dryer at 20 ^oC and when leave the dryer the moisture content must be less than 10%. Hot dry air at 100 ^oC is fed to the dryer. The dry bulb temperature of the exiting air is found to be 38 ^oC and the wet bulb temperature is 30 ^oC. The air exits from the dryer at a rate of 14 m^3 / Kg of wet chips entering the dryer.

- Draw a block diagram of the process and completely label it.
- Calculate the moisture content of the exiting chips and check whether it meets the design specification, i.e., the moisture content is less than 10%.
- If the dryer is operating adiabatically, what is the exit temperature of the dry chips. Given: Specific heat of bone dry wood chips is 2 kJ/(kg ^oC), specific heat of liquid water is 4.18 kJ/(kg ^oC) and the molecular weight of air 29. **Show all steps clearly (include input - output enthalpy table).**

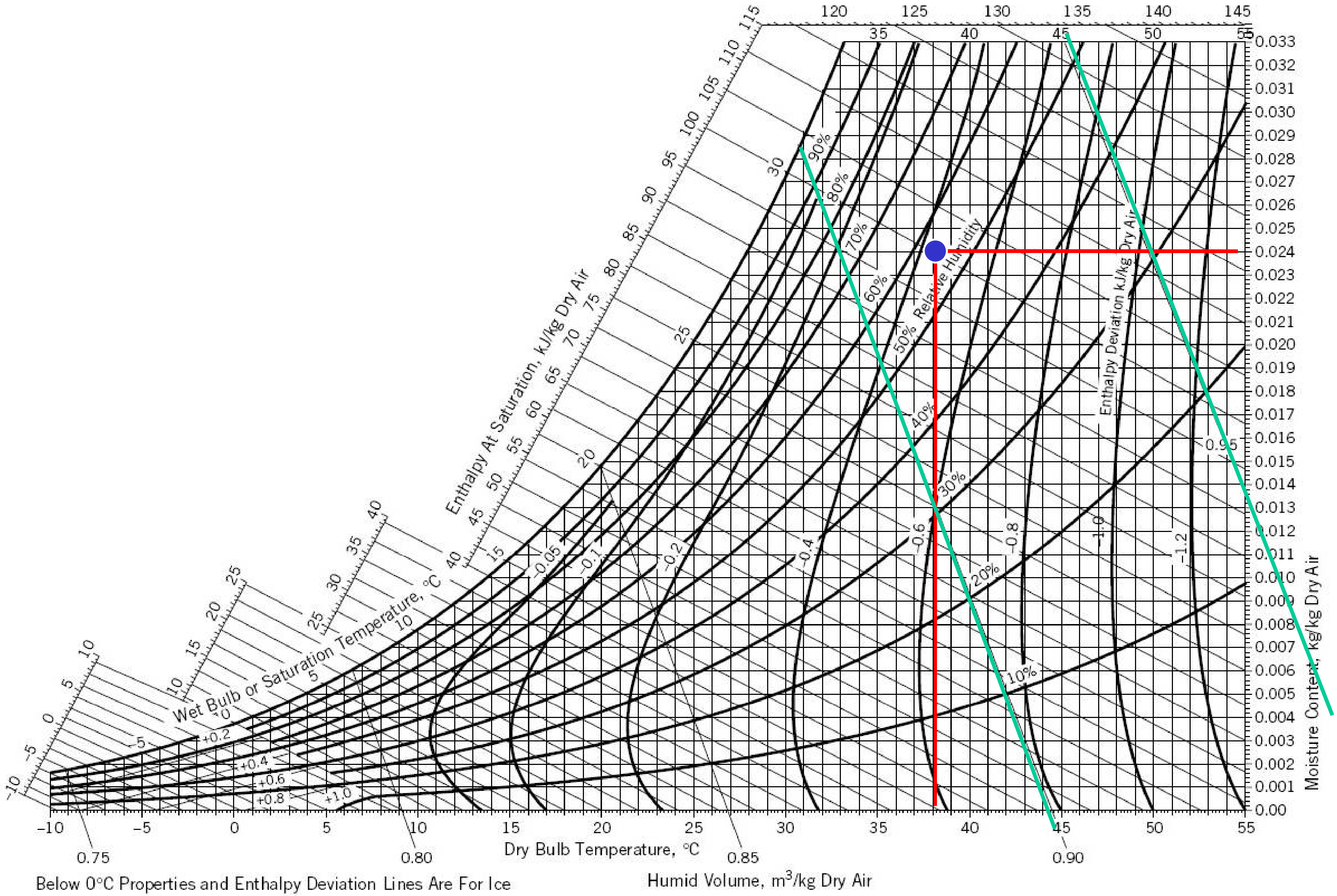


Figure 8.4-1 Psychrometric chart—SI units. Reference states: H_2O (L, 0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)