Thermodynamics: An Engineering Approach
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Yunus A. Çengel, Michael A. Boles
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CHAPTER 14

GAS–VAPOR MIXTURES AND AIR-CONDITIONING

Lecture slides by

Mehmet Kanoglu

DRY AND ATMOSPHERIC AIR

Atmospheric air: Air in the atmosphere containing some water vapor (or *moisture*).

Dry air: Air that contains no water vapor.

Water vapor in the air plays a major role in human comfort. Therefore, it is an important consideration in air-conditioning applications.

$$h_{\text{dry air}} = c_p T = (1.005\ \text{kJ/kg}\cdot{}^\circ\text{C})T \qquad (\text{kJ/kg})$$

$$\Delta h_{\text{dry air}} = c_p \Delta T = (1.005\ \text{kJ/kg}\cdot{}^\circ\text{C})\ \Delta T \qquad (\text{kJ/kg})$$

Water vapor in air behaves as if it existed alone and obeys the ideal-gas relation $Pv = RT$. Then the atmospheric air can be treated as an ideal-gas mixture:

$$P = P_a + P_v \qquad (\text{kPa})$$

P_a Partial pressure of dry air

P_v Partial pressure of vapor (vapor pressure)

Dry air

T, °C	c_p, kJ/kg·°C
−10	1.0038
0	1.0041
10	1.0045
20	1.0049
30	1.0054
40	1.0059
50	1.0065

FIGURE 14–1
The c_p of air can be assumed to be constant at 1.005 kJ/kg·°C in the temperature range −10 to 50°C with an error under 0.2 percent.

For water

h_g = 2500.9 kJ/kg at 0°C

$c_{p,avg}$ = 1.82 kJ/kg · °C at –10 to 50°C range

$$h_g(T) \cong 2500.9 + 1.82T \quad \text{(kJ/kg)} \quad T \text{ in °C}$$

$$h_g(T) \cong 1060.9 + 0.435T \quad \text{(Btu/lbm)} \quad T \text{ in °F}$$

$h = h(T)$ since water vapor is an ideal gas

$$h_v(T, \text{low } P) \cong h_g(T)$$

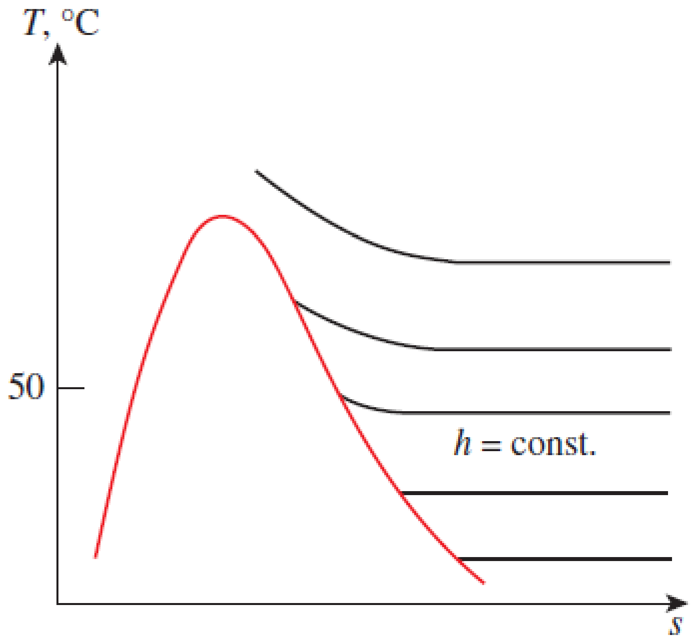


FIGURE 14–2
At temperatures below 50°C, the h = constant lines coincide with the T = constant lines in the superheated vapor region of water.

Water vapor

T, °C	h_g, kJ/kg Table A-4	h_g, kJ/kg Eq. 14-4	Difference, kJ/kg
–10	2482.1	2482.7	–0.6
0	2500.9	2500.9	0.0
10	2519.2	2519.1	0.1
20	2537.4	2537.3	0.1
30	2555.6	2555.5	0.1
40	2573.5	2573.7	–0.2
50	2591.3	2591.9	–0.6

FIGURE 14–3
In the temperature range –10 to 50°C, the h_g of water can be determined from Eq. 14–4 with negligible error.

SPECIFIC AND RELATIVE HUMIDITY OF AIR

Absolute or **specific humidity** (*humidity ratio*): The mass of water vapor present in a unit mass of dry air.

$$\omega = \frac{m_v}{m_a} \qquad \text{(kg water vapor/kg dry air)}$$

$$\omega = \frac{m_v}{m_a} = \frac{P_v V/R_v T}{P_a V/R_a T} = \frac{P_v/R_v}{P_a/R_a} = 0.622\frac{P_v}{P_a}$$

$$\omega = \frac{0.622 P_v}{P - P_v} \qquad \text{(kg water vapor/kg dry air)}$$

Saturated air: The air saturated with moisture.

Relative humidity: The ratio of the amount of moisture the air holds (m_v) to the maximum amount of moisture the air can hold at the same temperature (m_g).

$$\phi = \frac{m_v}{m_g} = \frac{P_v V/R_v T}{P_g V/R_v T} = \frac{P_v}{P_g}$$

$$P_g = P_{\text{sat @ } T}$$

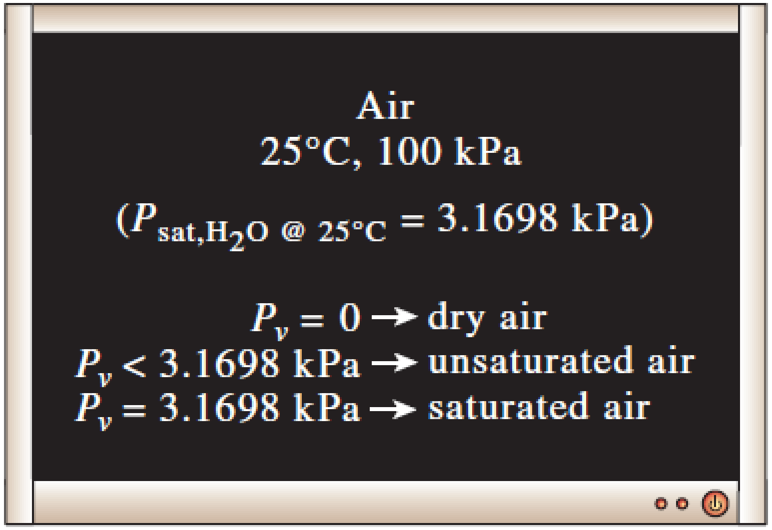


FIGURE 14–4
For saturated air, the vapor pressure is equal to the saturation pressure of water.

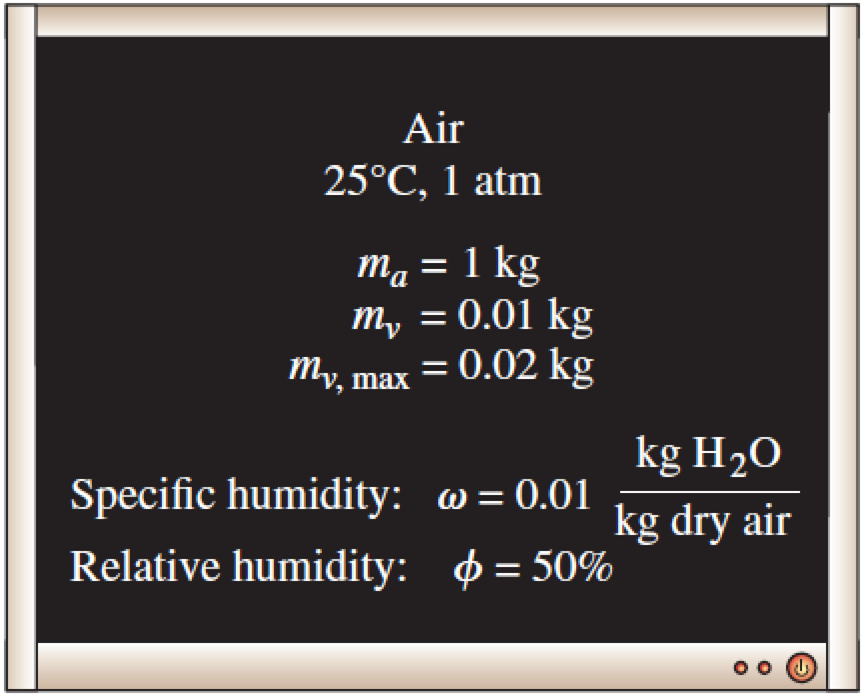


FIGURE 14–5
Specific humidity is the actual amount of water vapor in 1 kg of dry air, whereas relative humidity is the ratio of the actual amount of moisture in the air at a given temperature to the maximum amount of moisture air can hold at the same temperature.

$$\phi = \frac{\omega P}{(0.622 + \omega)P_g} \quad \text{and} \quad \omega = \frac{0.622\phi P_g}{P - \phi P_g}$$

What is the relative humidity of dry air and saturated air?

In most practical applications, the amount of dry air in the air–water-vapor mixture remains constant, but the amount of water vapor changes.

Therefore, the enthalpy of atmospheric air is expressed *per unit mass of dry air.*

$$H = H_a + H_v = m_a h_a + m_v h_v$$

$$h = \frac{H}{m_a} = h_a + \frac{m_v}{m_a} h_v = h_a + \omega h_v$$

$$h_v \cong h_g$$

$$h = h_a + \omega h_g \qquad \text{(kJ/kg dry air)}$$

Dry-bulb temperature:
The ordinary temperature of atmospheric air.

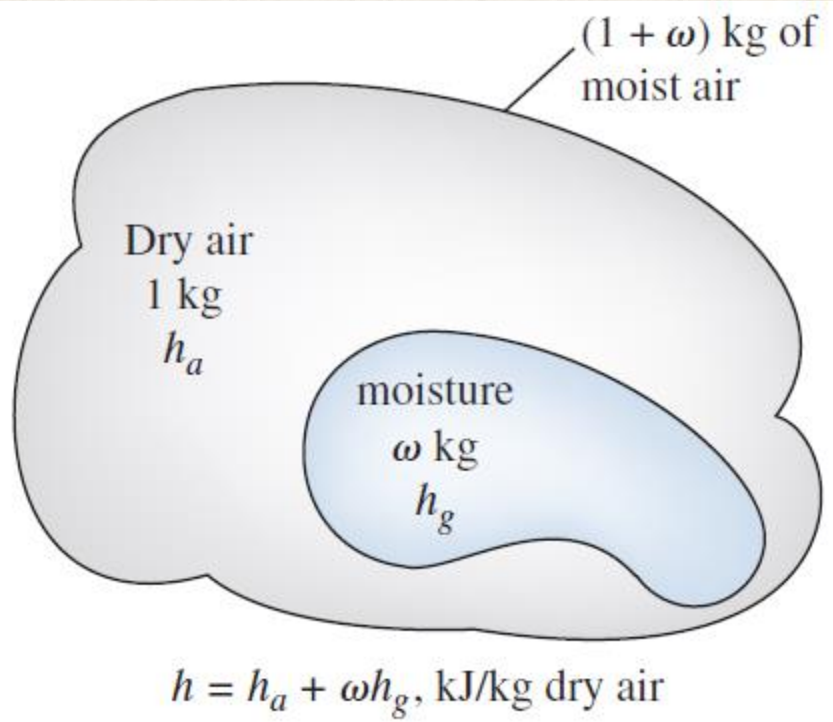


FIGURE 14–6
The enthalpy of moist (atmospheric) air is expressed per unit mass of dry air, not per unit mass of moist air.

DEW-POINT TEMPERATURE

Dew-point temperature T_{dp}: *The temperature at which condensation begins when the air is cooled at constant pressure* (*i.e.*, the saturation temperature of water corresponding to the vapor pressure.)

$$T_{dp} = T_{sat\ @\ P_v}$$

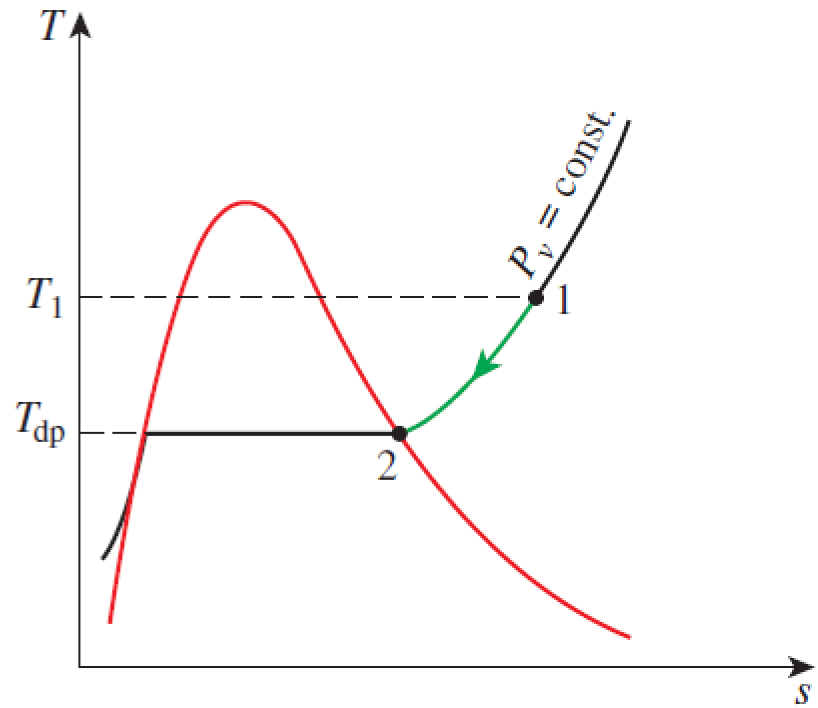
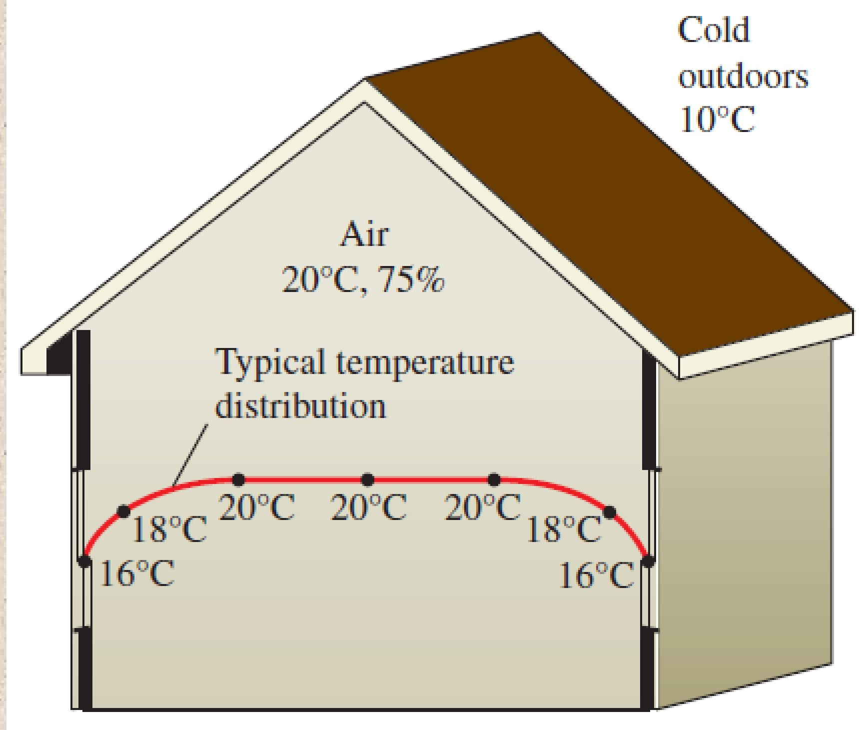


FIGURE 14–8
Constant-presssure cooling of moist air and the dew-point temperature on the *T-s* diagram of water.

FIGURE 14–9
When the temperature of a cold drink is below the dew-point temperature of the surrounding air, it "sweats."

EXAMPLE 14–2 **Fogging of the Windows in a House**

In cold weather, condensation frequently occurs on the inner surfaces of the windows due to the lower air temperatures near the window surface. Consider a house, shown in Fig. 14–10, that contains air at 20°C and 75 percent relative humidity. At what window temperature will the moisture in the air start condensing on the inner surfaces of the windows?



$$T_{dp} = T_{sat\ @\ P_v}$$

$$P_v = \phi P_{g\ @\ 20°C} = (0.75)(2.3392\ \text{kPa}) = 1.754\ \text{kPa}$$

$$T_{dp} = T_{sat\ @\ 1.754\ \text{kPa}} = \mathbf{15.4\ °C}$$

ADIABATIC SATURATION AND WET-BULB TEMPERATURES

$\dot{m}_{a_1} = \dot{m}_{a_2} = \dot{m}_a$ (The mass flow rate of dry air remains constant)

$\dot{m}_{w_1} + \dot{m}_f = \dot{m}_{w_2}$ (The mass flow rate of vapor in the air increases by an amount equal to the rate of evaporation $\dot{m}_f$)

$\dot{m}_a\omega_1 + \dot{m}_f = \dot{m}_a\omega_2$ → $\dot{m}_f = \dot{m}_a(\omega_2 - \omega_1)$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$\dot{m}_a h_1 + \dot{m}_f h_{f_2} = \dot{m}_a h_2$ → $\dot{m}_a h_1 + \dot{m}_a(\omega_2 - \omega_1)h_{f_2} = \dot{m}_a h_2$

$$h_1 + (\omega_2 - \omega_1)h_{f_2} = h_2$$

$$(c_p T_1 + \omega_1 h_{g_1}) + (\omega_2 - \omega_1)h_{f_2} = (c_p T_2 + \omega_2 h_{g_2})$$

$$\omega_1 = \frac{c_p(T_2 - T_1) + \omega_2 h_{fg_2}}{h_{g_1} - h_{f_2}} \qquad \omega_2 = \frac{0.622P_{g_2}}{P_2 - P_{g_2}}$$

The specific humidity (and relative humidity) of air can be determined from these equations by measuring the pressure and temperature of air at the inlet and the exit of an adiabatic saturator.

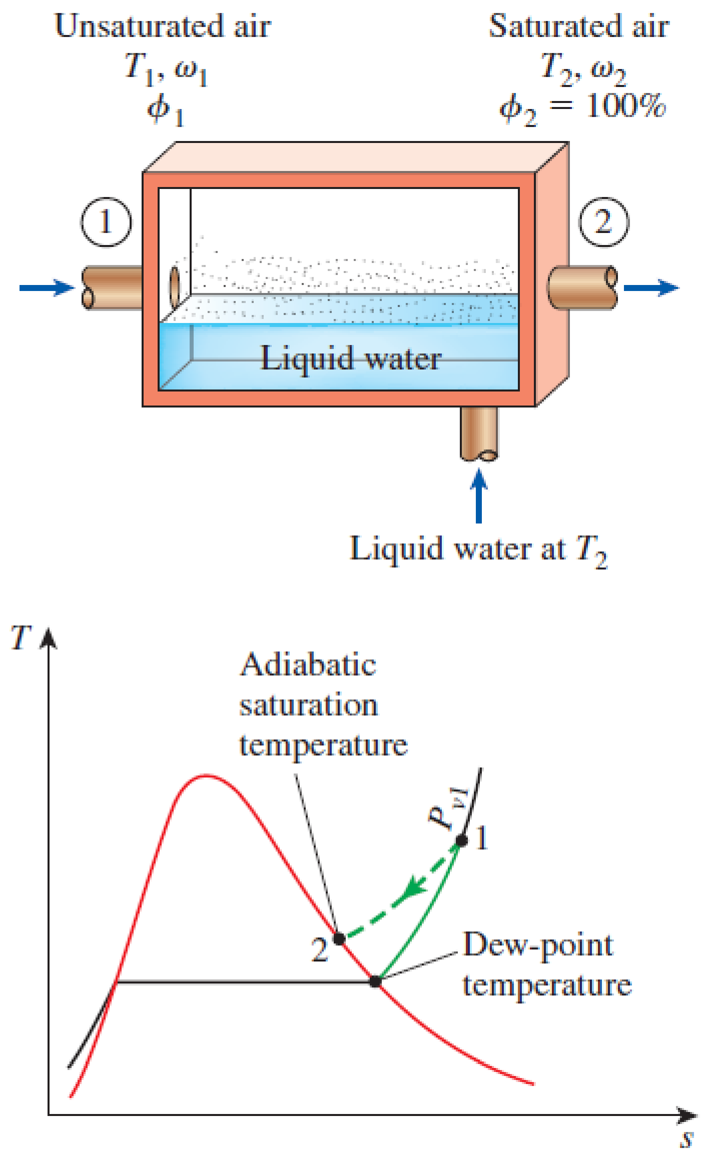


FIGURE 14–11
The adiabatic saturation process and its representation on a *T-s* diagram of water.

The adiabatic saturation process is not practical. To determine the absolute and relative humidity of air, a more practical approach is to use a thermometer whose bulb is covered with a cotton wick saturated with water and to blow air over the wick.

The temperature measured is the **wet-bulb temperature T_{wb}** and it is commonly used in A-C applications.

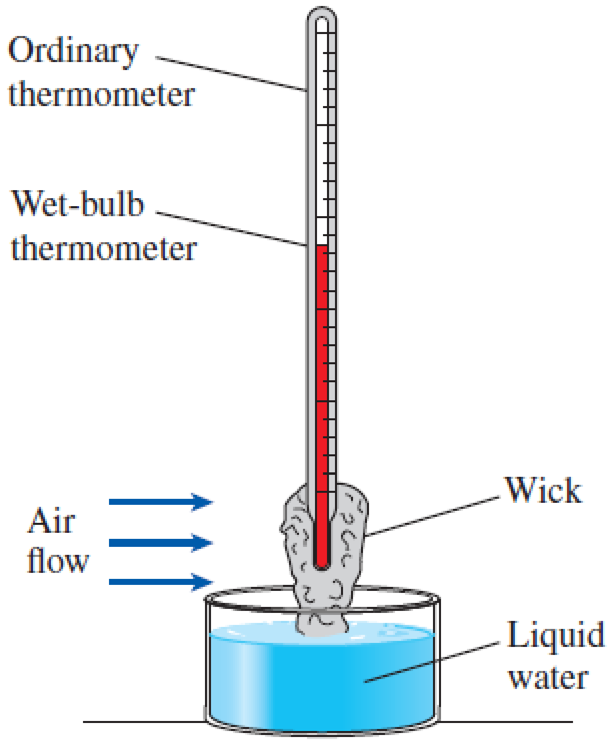


FIGURE 14–12
A simple arrangement to measure the wet-bulb temperature.

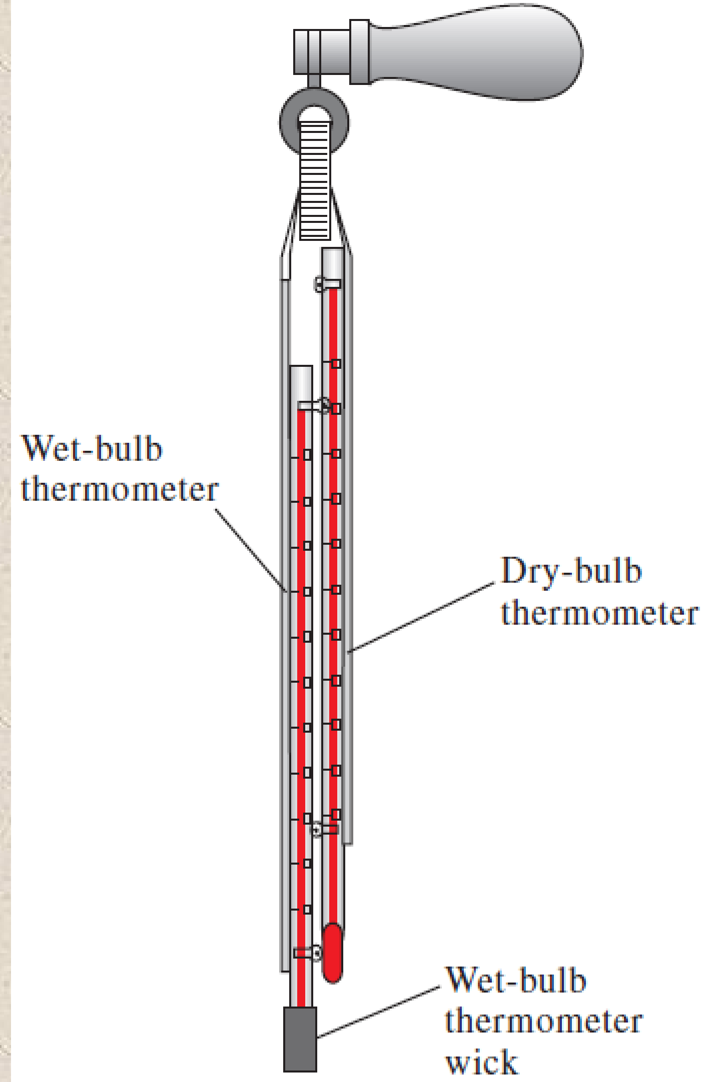


FIGURE 14–13
Sling psychrometer.

For air–water vapor mixtures at atmospheric pressure, T_{wb} is approximately equal to the adiabatic saturation temperature.

THE PSYCHROMETRIC CHART

Psychrometric charts: Present moist air properties in a convenient form. They are used extensively in A-C applications. The psychrometric chart serves as a valuable aid in visualizing the A-C processes such as heating, cooling, and humidification.

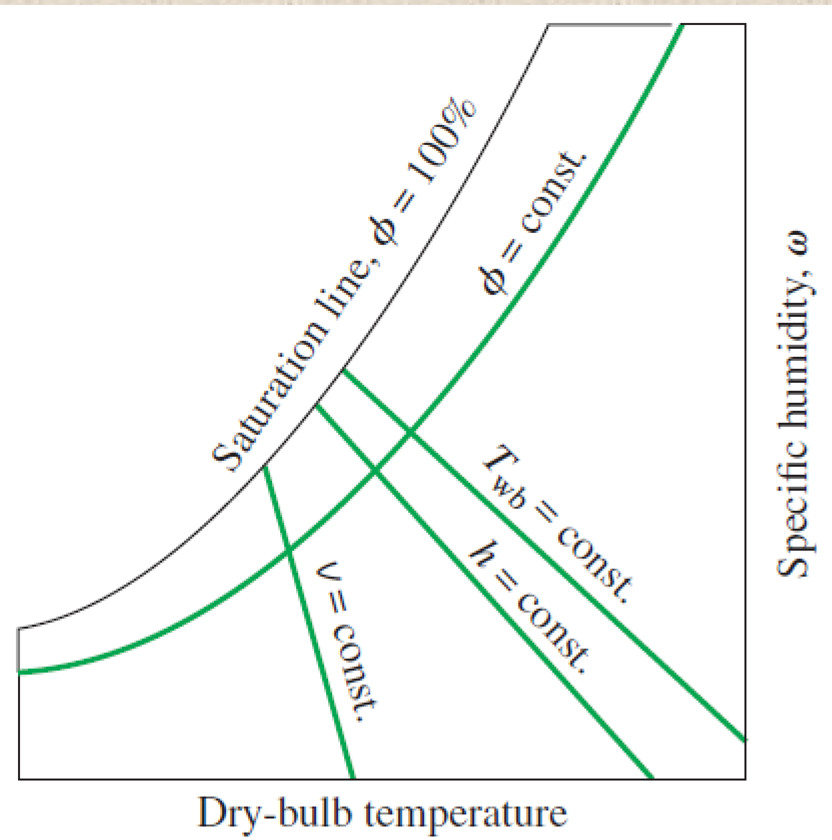


FIGURE 14–14
Schematic for a psychrometric chart.

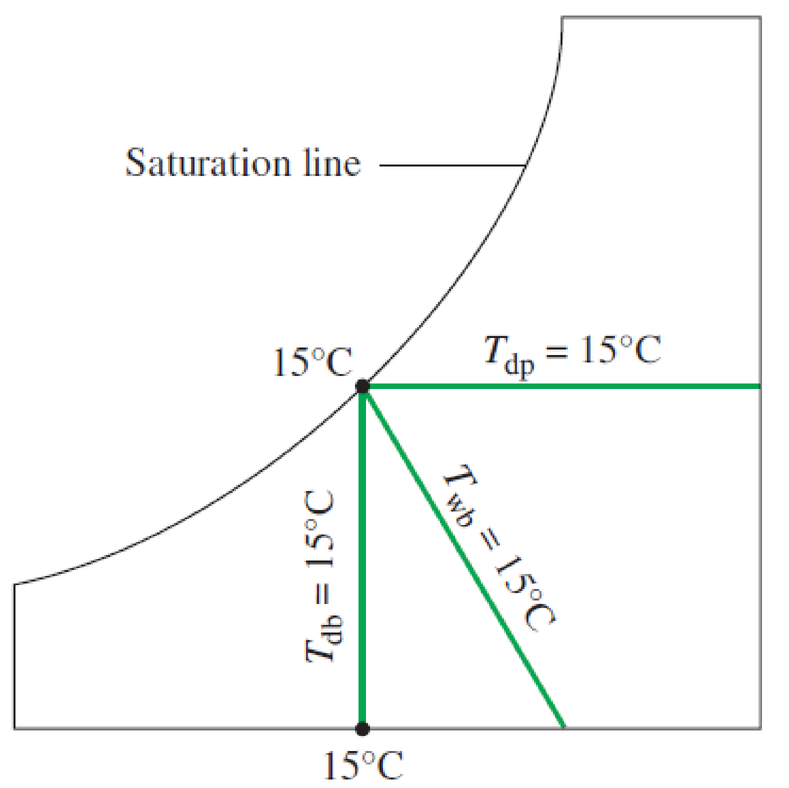


FIGURE 14–15
For saturated air, the dry-bulb, wet-bulb, and dew-point temperatures are identical.