on enthalpy in the calculations of $\dot{H}_1$ through $\dot{H}_4$. The heat capacity and latent heat data needed to calculate the outlet enthalpies are obtained from Tables B.1 and B.2.

The formulas and values of the unknown specific enthalpies are given below. Convince yourself that the formulas represent $\Delta H$ for the transitions from the reference states to the process states.

$$\dot{H}_1 = \int_{10^0^\circ C}^{50^\circ C} (C_p)_{c_6H_{14}(0)} \, dT = 5.332 \text{ kJ/mol}$$

$$\dot{H}_2 = \int_{10^0^\circ C}^{50^\circ C} (C_p)_{c_6H_{14}(0)} \, dT = 6.340 \text{ kJ/mol}$$

$$\dot{H}_3 = \int_{10^0^\circ C}^{-80.1^\circ C} (C_p)_{c_6H_{14}(0)} \, dT + (\Delta \dot{H}_3)_{c_6H_{14}(80.1^\circ C)} + \int_{-80.1^\circ C}^{50^\circ C} (C_p)_{c_6H_{14}(\nu)} \, dT$$

$$= 37.52 \text{ kJ/mol}$$

$$\dot{H}_4 = \int_{10^0^\circ C}^{-110.85^\circ C} (C_p)_{c_6H_{14}(0)} \, dT + (\Delta \dot{H}_4)_{c_6H_{14}(110.62^\circ C)} + \int_{-110.85^\circ C}^{50^\circ C} (C_p)_{c_6H_{14}(\nu)} \, dT$$

$$= 42.93 \text{ kJ/mol}$$

The energy balance is

$$Q = \Delta H = \sum_{\text{out}} n_i \dot{H}_i - \sum_{\text{in}} n_i \dot{H}_i \implies Q = 17.7 \text{ kJ}$$

**CREATIVITY EXERCISE**

A gas emerges from a stack at 1200°C. Rather than being released directly to the atmosphere, it can be passed through one or several heat exchangers, and the heat it loses can be put to use in a variety of ways. Think of as many uses of this heat as you can. (Example: During the winter, pass the gas through a series of radiators, thereby getting free heating.)

**8.4d Psychrometric Charts**

On a psychrometric chart (or humidity chart) several properties of a gas–vapor mixture are cross-plotted, providing a concise compilation of a large quantity of physical property data. The most common of these charts—that for the air-water system at 1 atm—is used extensively in the analysis of humidification, drying, and air-conditioning processes.

A psychrometric chart in SI units for the air–water system at 1 atm is shown in Figure 8.4-1, and a second chart in American engineering units is shown in Figure 8.4-2. Charts that cover wider temperature ranges are given on pp. 12-4 through 12-7 of Perry’s Chemical Engineers’ Handbook (see footnote 5).

The following paragraphs define and describe the different properties of humid air at 1 atm that appear on the psychrometric chart. Once you know the values of any two of these properties, you can use the chart to determine the values of the others. We will use the abbreviation DA for dry air.

- **Dry-bulb temperature**, $T$—the abscissa of the chart. This is the air temperature as measured by a thermometer, thermocouple, or other conventional temperature-measuring instrument.

- **Absolute humidity**, $h_a$ [kg H$_2$O/(v)/kg DA] (called moisture content on Figure 8.4-1)—the ordinate of the chart.

  This ratio can easily be calculated from or converted to the mass fraction of water. If, for example, the absolute humidity is 0.0150 kg H$_2$O/kg DA, then for every kilogram of dry air there is 0.015 kg of water vapor, for a total of 1.015 kg. The mass fraction of water is $(0.0150 \text{ kg H}_2\text{O})/(1.015 \text{ kg humid air}) = 0.0148 \text{ kg H}_2\text{O/kg}$. 

- **Relative humidity**, $r_h$ (the ratio of the actual partial pressure of water vapor to the saturation partial pressure at the same temperature and barometric pressure). 

- **Dew point**, $T_d$—the temperature at which the air becomes saturated with water vapor. For a given partial pressure of water vapor, the maximum temperature is the dew point. 

- **Saturated air pressure, $P_s$**—the maximum pressure at which water vapor can exist in air at a given temperature and barometric pressure.

- **Humid-bulb temperature, $T_b$**—the temperature of a thermometer whose bulb is covered with a wet cloth (usually a 100% cotton cloth), which is always at the saturation temperature of the water vapor present. This thermometer is also called a wet-bulb thermometer.

- **Wet-bulb temperature, $T_w$**—the temperature of the wet-bulb thermometer. This is the temperature at which the air is saturated with water vapor. It may be either a dry-bulb thermometer or a wet-bulb thermometer.

- **Psychrometer**—a device that consists of two thermometers: one covered with a wet cloth (wet-bulb), the other being the dry-bulb thermometer. A psychrometer is used to determine psychrometric properties of air, such as humidity and dew point.
Figure 8.4-1 Psychrometric chart—SI units. Reference states: H$_2$O (0°C, 1 atm), dry air (0°C, 1 atm). (Reprinted with permission of Carrier Corporation.)
• **Relative humidity,** \( h_r = \left[100 \times \frac{p_{\text{H}_2\text{O}}}{p^*_{\text{H}_2\text{O}}(T)}\right] \).

Curves on the psychrometric chart correspond to specified values of \( h_r \) (100%, 90%, 80%, etc.). The curve that forms the left boundary of the chart is the **100% relative humidity curve**, also known as the **saturation curve**.

• **Dew point,** \( T_{dp} \)—the temperature at which humid air becomes saturated if it is cooled at constant pressure.

The dew point of humid air at a given point on the psychrometric chart can easily be determined. For example, locate the point on Figure 8.4-1 corresponding to air at 29°C and 20% relative humidity. Cooling this air at constant pressure (= 1 atm) corresponds to moving horizontally (at constant absolute humidity) to the saturation curve. \( T_{dp} \) is the temperature at the intersection, or 4°C. (Verify this statement.)

• **Humid volume,** \( V_H \) (m³/kg DA).

The humid volume is the volume occupied by 1 kg of dry air plus the water vapor that accompanies it. Lines of constant humid volume on the psychrometric chart are steep and have negative slopes. On Figure 8.4-1, humid volume lines are shown corresponding to 0.75, 0.80, 0.85, and 0.90 m³/kg dry air.

To determine the volume of a given mass of wet air using the psychrometric chart, you must first determine the corresponding mass of dry air from the absolute humidity, then multiply this mass by \( V_H \). Suppose, for example, you wish to know the volume occupied by 150 kg of humid air at \( T = 30°C \) and \( h_r = 30% \). From Figure 8.4-1, \( h_r = 0.0080 \text{ kg H}_2\text{O(v)/kg DA} \) and \( V_H = 0.87 \text{ m}^3/\text{kg DA} \). The volume may then be calculated as

\[
V = \frac{150 \text{ kg humid air} \times 1.00 \text{ kg DA}}{1.008 \text{ kg humid air/ kg DA} \times 0.87 \text{ m}^3} = 129 \text{ m}^3
\]

(In this calculation, we used the fact that if the absolute humidity is 0.008 kg H₂O/kg DA, then 1 kg DA is accompanied by 0.008 kg water for a total of 1.008 kg humid air.)

• **Wet-bulb temperature,** \( T_{wb} \).

This quantity is best defined in terms of how it is measured. A porous material like cloth or cotton is soaked in water and wrapped around the bulb of a thermometer to form a **wick**, and the thermometer is placed in a stream of flowing air, as in the figure shown below.⁹ Evaporation of water from the wick into the flowing air is accompanied by a transfer of heat from the bulb, which in turn causes a drop in the bulb temperature and hence in the thermometer reading.¹⁰ Provided that the wick remains moist, the bulb temperature falls to a certain value and remains there. The final temperature reading is the wet-bulb temperature of the air flowing past the wick.

---

⁹Alternatively, the thermometer may be mounted in a **sling psychrometer** and whirled around in stationary air.

¹⁰Think about what happens when you step out of a shower or swimming pool. Water evaporates, your skin temperature drops, and you feel cold, even if you felt perfectly comfortable when you were dry.
The wet-bulb temperature of humid air depends on both the dry-bulb temperature and the moisture content of the air. If the air is saturated (100% relative humidity), no water evaporates from the wick, and the wet-bulb and dry-bulb temperatures are the same. The lower the humidity, the greater the difference between the two temperatures.

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. The constant wet-bulb temperature lines for air-water at 1 atm appear on Figures 8.4-1 and 8.4-2 as lines with negative slopes extending beyond the saturation curve that are less steep than the lines of constant humid volume. The value of $T_{wb}$ corresponding to a given line can be read at the intersection of the line with the saturation curve.

For example, suppose you wish to determine the wet-bulb temperature of air at 30°C (dry bulb) with a relative humidity of 30%. Locate the point on Figure 8.4-1 at the intersection of the vertical line corresponding to $T = 30°C$ and the curve corresponding to $h_r = 30\%$. The diagonal line through the point is the constant wet-bulb temperature line for air at the given condition. Follow that line upward to the left until you reach the saturation curve. The temperature value you read on the curve (or vertically down from it on the abscissa) is the wet-bulb temperature of the air. You should get a value of 18°C. This means that if you wrap a wet wick around a thermometer bulb and blow air with $T = 30°C$ and $h_r = 30\%$ past the bulb, the thermometer reading will drop and eventually stabilize at 18°C.

**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. The reference states are liquid water at 1 atm and 0°C (32°F) and dry air at 1 atm and 0°C (Figure 8.4-1) or 0°F (Figure 8.4-2). To determine the enthalpy from the chart, follow the constant wet-bulb temperature line from the saturation curve at the desired temperature to the enthalpy scale.

For example, saturated air at 25°C and 1 atm—which has an absolute humidity $h_w = 0.0202$ kg H₂O/kg DA—has a specific enthalpy of 76.5 kJ/kg DA. (Verify these values of both $h_w$ and $H$ 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.

\[
1.00 \text{ kg DA(0°C)} \rightarrow 1 \text{ kg DA(25°C)}
\]

\[
\Delta H_{\text{air}} = (1.00 \text{ kg DA}) \left( \frac{1 \text{ kmol}}{29.0 \text{ kg}} \right) \int_{0}^{25} C_{p, \text{air}}(T) \, dT \left( \frac{\text{kJ}}{\text{kmol}} \right) = 25.1 \text{ kJ}
\]

\[
0.0202 \text{ kg H₂O(0°C)} \rightarrow 0.0202 \text{ kg H₂O(25°C)}
\]

\[
\Delta H_{\text{water}} = (0.0202 \text{ kg}) \left( H_{\text{H₂O(25°C)}} - H_{\text{H₂O(0°C)}} \right) \left( \frac{\text{kJ}}{\text{kg}} \right) = 51.4 \text{ kJ}
\]

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

**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.

The basis for the construction of the psychrometric chart is the Gibbs phase rule (Section 6.3a), which states that specifying a certain number of the intensive variables (temperature, pressure, specific volume, specific enthalpy, component mass or mole fractions, etc.) of a system automatically fixes the value of the remaining intensive variables. Humid air contains one phase and two components, so that from Equation 6.2-1 the number of degrees of freedom is

\[ F = 2 + 2 - 1 = 3 \]

Specifying three intensive variables therefore fixes all other system properties. If the system pressure is fixed at 1 atm, then all other properties may be plotted on a two-dimensional plot, such as those shown in Figures 8.4-1 and 8.4-2.

**EXAMPLE 8.4.5**

**The Psychrometric 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 m³ of air at these conditions.

**SOLUTION**

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

1. Reading from the chart,

   \[ h_a = 0.0048 \text{ kg H}_2\text{O/kg DA} \]
   \[ T_{wb} = 19°C \]
   \[ \bar{V}(\text{m}^3/\text{kg DA}) = 0.895 \text{ (curve not shown)} \]

   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 \( h_a = 0.0048 \) and the saturation curve, or

   \[ T_{dp} = 3°C \]

---

11Since the components of dry air do not condense and are present in fixed proportion, dry air may be considered a single species (designated DA) in humidity calculations.
The specific enthalpy of saturated air at $T_{wb} = 19^\circ C$ 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 $\dot{H}$ as

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

$$\downarrow$$

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

2. **Moles of humid air.** From Figure 8.4-1, the humid volume of the air is 0.897 m³/kg DA. We therefore calculate

\[
\begin{array}{ccc}
150 \text{ m}^3 & 1.00 \text{ kg DA} & 0.0048 \text{ kg H}_2\text{O} \\
0.897 \text{ m}^3 & 1.00 \text{ kg DA} & \boxed{0.803 \text{ kg H}_2\text{O}}
\end{array}
\]

The psychrometric chart can be used to simplify the solution of material and energy balance problems for constant-pressure air-water systems, at the expense of some precision. Note the following points:

1. Heating or cooling humid air at temperatures above the dew point corresponds to horizontal movement on the psychrometric chart. The ordinate on the chart is the ratio kg H₂O/kg dry air, which does not change as long as no condensation occurs.

2. If superheated humid air is cooled at 1 atm, the system follows a horizontal path to the left on the chart until the saturation curve (dew point) is reached; thereafter, the gas phase follows the saturation curve.

3. Since the psychrometric chart plots the mass ratio kg H₂O/kg dry air rather than the mass fraction of water, it is usually convenient to assume a quantity of dry air in a feed or product stream as a basis of calculation if the chart is to be used in the solution.

**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 ft³/min of humid air at the final condition.

**SOLUTION**

**Basis: 1 lbm Dry Air**

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.

\[\text{AIR COOLER}\]

1 lbm DA, 51°F
\[m_{l}(\text{lbm H}_2\text{O}(v)) \quad H_{l}^{*}(\text{Btu/lbm DA})\]

1 lbm DA, 51°F
\[m_{l}(\text{lbm H}_2\text{O}(v)) \quad H_{l}^{*}(\text{Btu/lbm DA})\]

\[Q \quad (\text{Btu})\]

**Note:** In labeling the outlet gas stream, we have implicitly written a balance on dry air.

---

**Footnote:** In assuming this basis, we are temporarily ignoring the specification of the volumetric flow rate at the outlet. After the process is balanced for the assumed basis, we will scale up to an outlet flow rate of 1000 ft³/min.