

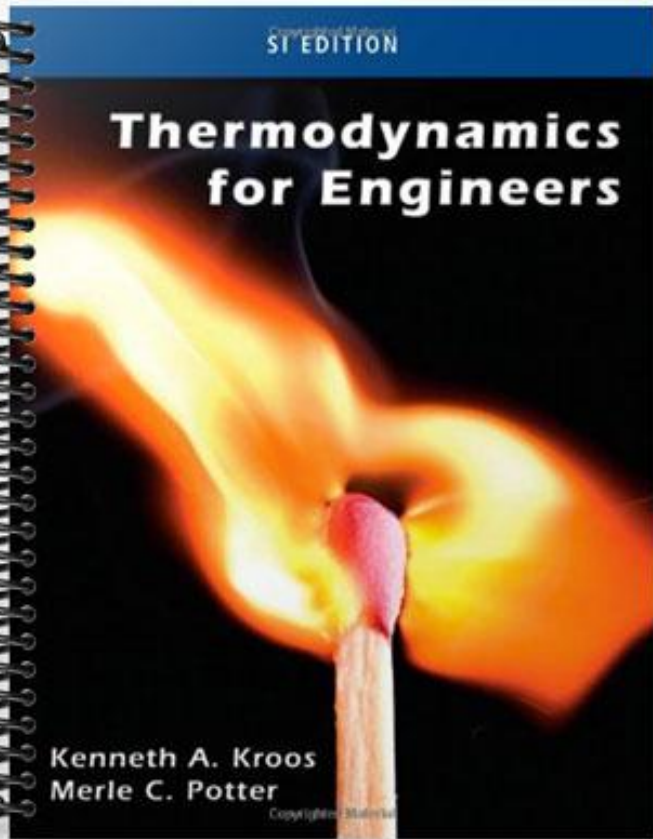
# SOLUTIONS MANUAL

SI EDITION

## Thermodynamics for Engineers

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## Chapter 2 Solutions

- 2.1 (D)** Pressure and temperature are dependent during phase change and independent when in a single phase.
- 2.2 (B)** Sublimation is the direct conversion of a solid to a gas. To observe this process, set a piece of dry ice out on a table top.
- 2.3 (B)** From Table B-1 at 9000 m, the atmospheric pressure is 30% of atmospheric pressure at sea level which is 30 kPa. From Table C-2 the saturation temperature for 30 kPa or 0.03 MPa is 69.1°C.
- 2.4 (A)** The water is subcooled. If it were saturated it would be at 100°C and cook you.
- 2.5 (A)** From Table C-1 at 200°C and  $v = 0.002 \text{ m}^3/\text{kg}$ , the water is a saturated mixture. At 200°C and  $v = 0.2 \text{ m}^3/\text{kg}$  the water is a superheated vapor. Graph (A) describes this process. Constant pressure goes up to the right and constant temperature goes down to the right.
- 2.6 (D)** The mass is 2 kg and the volume is  $0.08 \text{ m}^3$ . The specific volume is

$$v = \frac{0.08 \text{ m}^3}{2 \text{ kg}} = 0.04 \text{ m}^3/\text{kg}$$

From Table C-1 we get  $v_f = 0.001156 \text{ m}^3/\text{kg}$  and  $v_g = 0.1274 \text{ m}^3/\text{kg}$ . Calculating the quality we get

$$x = \frac{v - v_f}{v_g - v_f} = \frac{0.04 - 0.001156}{0.1274 - 0.001156} = \underline{0.31}$$

- 2.7 (A)** From Table C-3 for  $P = 10 \text{ MPa}$  and  $T = 300^\circ\text{C}$ , the water is subcooled since saturation temperature at 10 MPa is 311°C. This means that the specific volume is  $v_f$  at 300°C. From Table C-1 we get

$$v_f = 0.001404 \text{ m}^3/\text{kg}. \quad \therefore V = 20 \text{ kg} \times 0.001404 \text{ m}^3/\text{kg} = \underline{0.028 \text{ m}^3}$$

- 2.8 (C)** The specific volume at 400°C and 4 MPa is  $v_1 = 0.0734 \text{ m}^3/\text{kg} = v_2$ . The volume doesn't change if it is rigid. Either Table C-1 or C-2 will contain the desired pressure. Table C-1 is preferred since the  $v$ -entries are closer together. The entry at 230°C is  $v_1 = 0.072 \text{ m}^3/\text{kg}$ , quite close to  $0.073 \text{ m}^3/\text{kg}$ . Interpolation need not be accurate in order to select the correct answer:  $P_2 \cong 2.8 \text{ MPa}$ .

- 2.9 (A)** ( $1000 \text{ liters} = 1 \text{ m}^3$ )  $V = 3 \text{ L} = 0.003 \text{ m}^3$ . Remember that quality is calculated on a mass basis, not a volume basis. From Table C-1 for a temperature of 200°C we get  $v_f = 0.001156 \text{ m}^3/\text{kg}$  and  $v_g = 0.1274 \text{ m}^3/\text{kg}$ . The liquid mass =  $V_{\text{liquid}}/v_f = 0.001 \text{ m}^3/0.001156 \text{ m}^3/\text{kg} = 0.865 \text{ kg}$ . The vapor mass =  $V_{\text{vapor}}/v_g = 0.002 \text{ m}^3/0.1274 \text{ m}^3/\text{kg} = 0.0157 \text{ kg}$ . Now we can calculate the quality:

$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}} = \frac{0.0157 \text{ kg}}{0.0157 \text{ kg} + 0.865 \text{ kg}} = 0.018 = \underline{1.8\%}$$

**2.10 (B)** Average the  $h$ -values between 6 MPa and 7 MPa for 600°C and 700°C in Table C-3. There is only a small change in enthalpy with pressure so a calculator is not needed:

$$\text{At } 600^\circ\text{C: } \left. \begin{array}{cc} 6 & 7 \\ 3658 & 3650 \end{array} \right\} h = 3654 \quad \text{At } 700^\circ\text{C: } \left. \begin{array}{cc} 6 & 7 \\ 3894 & 3888 \end{array} \right\} h = 3891$$

Now, interpolate between 3654 and 3891:

$$h = \frac{3}{4}(3891 - 3654) + 3654 = \underline{3832 \text{ kJ/kg}}$$

**2.11 (A)** The tire is a torus with a minor radius  $r$  of 0.01 m and a major radius  $R$  of 1 m. The volume of the tire is the circumference times the area of the tire:

$$V = \pi D \times A = \pi \times 1 \times (\pi \times 0.01^2) = 9.87 \times 10^{-4} \text{ m}^3$$

Treat air as an ideal gas (to check the units, use kPa = kN/m<sup>2</sup> and kJ = kN·m):

$$m = \frac{PV}{RT} = \frac{(500 \text{ kPa})(9.87 \times 10^{-4} \text{ m}^3)}{\left(0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}\right)(293 \text{ K})} = \underline{0.0059 \text{ kg}}$$

**2.12 (C)** The pressure in the cylinder can be found using the ideal gas law:

$$P = \frac{mRT}{V} = \frac{0.02 \times 0.287 \times 313}{\pi \times 0.125^2 \times 0.20} = 183 \text{ kPa} \quad \text{or} \quad 83 \text{ kPa gage}$$

The pressure balances the weight of the piston but we must use the gage pressure or add a force on the top of the piston due to the atmospheric pressure:

$$W = PA = 83 \,000 \times \pi \times 0.125^2 = \underline{4070 \text{ N}}$$

**2.13 (A)** Because the temperature is so low and the pressure quite high, we anticipate non-ideal gas behavior. So, let's approximate the  $Z$ -factor using Appendix G:

$$P_R = \frac{P}{P_{cr}} = \frac{3}{3.77} = 0.80, \quad T_R = \frac{T}{T_{cr}} = \frac{130}{133} = 0.98. \quad \therefore Z = 0.59$$

$$m = \frac{PV}{ZRT} = \frac{3000 \times 0.020}{0.59 \times 0.287 \times 130} = \underline{2.73 \text{ kg}}$$

**2.14 (B)** For an ideal gas  $\rho = \frac{1}{v} = \frac{P}{RT}$ .  $\rho_{\text{outside}} = \frac{100}{0.287 \times 248} = 1.405 \text{ kg/m}^3$

$$\rho_{\text{inside}} = \frac{100}{0.287 \times 295} = 1.181 \text{ kg/m}^3$$

$$\text{Difference} = 1.405 - 1.181 = \underline{0.224 \text{ kg/m}^3}$$

**2.15 (B)**  $C_p = \frac{\Delta h}{\Delta T}\bigg|_p = \frac{3330.3 - 3092.5}{450 - 350} = 2.38 \text{ kJ/kg}\cdot^\circ\text{C}$  using a central-difference approximation.

Compare with the value from Table B-2 where steam is treated as an ideal gas (near atmospheric temperature and low pressure).

**2.16 (D)** From Table B-2:  $C_p = 1.872 \text{ kJ/kg}\cdot\text{K}$ .  $\therefore \Delta h = C_p \Delta T = 1.872 \times 400 = 748.8 \text{ kJ/kg}$   
From Table C-3  $h_{200} = 2870.5 \text{ kJ/kg}$  and  $h_{600} = 3704 \text{ kJ/kg}$

$$\Delta h = 3704 - 2870.5 = 833.5 \text{ kJ/kg}$$

$$\% \text{difference} = \frac{748.8 - 833.5}{833.5} \times 100\% = \underline{-10\%}$$

**2.17 (A)** The enthalpy change to warm up the ice is found by approximating  $C_p$  to be  $2.05 \text{ kJ/kg}\cdot^\circ\text{C}$  between  $-20^\circ\text{C}$  and  $0^\circ\text{C}$  (see Table B-4):

$$\Delta H_{\text{ice}} = m\Delta h = 10 \times 2.05 \times 20 = 410 \text{ kJ}$$

The ice is now at  $0^\circ\text{C}$  at which state it melts, requiring the heat of fusion,  $330 \text{ kJ/kg}$ :

$$\Delta H_{\text{melt}} = m\Delta h_{\text{fusion}} = 10 \times 330 = 3300 \text{ kJ}$$

If the temperature of the water is now raised from  $0^\circ\text{C}$  to  $100^\circ\text{C}$ , the enthalpy change is found using  $C_p = 4.18 \text{ kJ/kg}\cdot^\circ\text{C}$  to be

$$\Delta H_{\text{melt}} = m\Delta h_{\text{water}} = mC_p\Delta T = 10 \times 4.18 \times 100 = 4180 \text{ kJ}$$

Finally, the steam is superheated to  $200^\circ\text{C}$ . From Table C-3 at  $P = 0.1 \text{ MPa}$ , we find

$$\Delta H = m\Delta h = 10 \times (2875.3 - 2675.5) = 1998 \text{ kJ}$$

The total enthalpy change to warm the ice, melt the ice, vaporize the water, and superheat the steam is

$$\Delta H = 410 + 3330 + 4180 + 1998 = \underline{9920 \text{ kJ}}$$

**2.18 a)** From Table C-1 for  $T = 140^\circ\text{C}$ ,  $P_{\text{sat}} = 0.3613 \text{ MPa} = \underline{361 \text{ kPa}}$

**b)** For  $T = 200^\circ\text{C}$ ,  $P_{\text{sat}} = 1.554 \text{ MPa} = \underline{1554 \text{ kPa}}$

**c)** For  $T = 320^\circ\text{C}$ ,  $P_{\text{sat}} = 11.27 \text{ MPa} = \underline{11\,270 \text{ kPa}}$

**2.19 a)** From Table C-2 for  $P = 85 \text{ kPa}$ ,  $T_{\text{sat}}$  is calculated by interpolating between  $80 \text{ kPa}$  and  $100 \text{ kPa}$ :

$$\frac{T_{\text{sat}} - 93.5^\circ}{99.6^\circ - 93.5^\circ} = \frac{85 \text{ kPa} - 80 \text{ kPa}}{100 \text{ kPa} - 80 \text{ kPa}} \quad T_{\text{sat}} = \underline{95.02^\circ\text{C}}$$

**b)** For  $P = 200 \text{ kPa}$ ,  $T_{\text{sat}} = \underline{120.2^\circ\text{C}}$

**c)** For  $P = 700 \text{ kPa}$ , we need to interpolate between  $300 \text{ kPa}$  and  $400 \text{ kPa}$ ,

$$T_{\text{sat}} = \frac{133.5 + 143.6}{2} = \underline{139^\circ\text{C}}$$

**2.20** For a temperature of 90°C, we use Table C-1 to find  $P_{\text{sat}} = 0.07013 \text{ MPa} = 70.13 \text{ kPa}$ . From Table B-1 we see that  $P/P_0 = 0.7031$  between 2000 m and 3000 m of altitude. We interpolate to find the exact altitude  $h$ :

$$\frac{h - 2000 \text{ m}}{3000 \text{ m} - 2000 \text{ m}} = \frac{0.7031 - 0.7846}{0.6920 - 0.7846} \quad \therefore h = \underline{2880 \text{ m}}$$

**2.21** We use Table C-1 to find the pressure and Table C-2 to find the corresponding saturation temperature.

a) For  $h = 3600 \text{ m}$  we get  $P/P_0$  by interpolating between 3000 m and 4000 m.

$$\frac{\frac{P}{P_0} - 0.6920}{0.6085 - 0.6920} = \frac{3600 \text{ m} - 3000 \text{ m}}{4000 \text{ m} - 3000 \text{ m}} \quad \therefore P/P_0 = 0.642$$

$P = 0.642 \times 100 \text{ kPa} = 64.2 \text{ kPa}$ . For this pressure we get the saturation temperature by interpolation between 60 kPa and 80 kPa:

$$\frac{T_{\text{sat}} - 85.9^\circ}{93.5^\circ - 85.9^\circ} = \frac{64.2 \text{ kPa} - 60 \text{ kPa}}{80 \text{ kPa} - 60 \text{ kPa}} \quad \therefore T_{\text{sat}} = \underline{87.5^\circ\text{C}}$$

b) For  $h = 6000 \text{ m}$  we get  $P/P_0 = 0.466$  and so  $P = 0.466 \times 100 \text{ kPa} = 46.6 \text{ kPa}$ . We have to interpolate between 40 and 60 kPa to find the saturation temperature:

$$\frac{T_{\text{sat}} - 75.9^\circ}{85.9^\circ - 75.9^\circ} = \frac{46.6 \text{ kPa} - 40 \text{ kPa}}{60 \text{ kPa} - 40 \text{ kPa}} \quad \therefore T_{\text{sat}} = \underline{79.2^\circ\text{C}}$$

c) For  $h = 9600 \text{ m}$  we have to interpolate between 8000 m and 10 000 m to get  $P/P_0$ .

$$\frac{\frac{P}{P_0} - 0.3519}{0.2615 - 0.3519} = \frac{9600 \text{ m} - 8000 \text{ m}}{10000 \text{ m} - 8000 \text{ m}} \quad \therefore P/P_0 = 0.279 \text{ and } P = 0.279 \times 100 \text{ kPa} \\ = 27.9 \text{ kPa}$$

We have to interpolate between 20 and 30 kPa to find the saturation temperature:

$$\frac{T_{\text{sat}} - 60.1^\circ}{69.1^\circ - 60.1^\circ} = \frac{27.9 \text{ kPa} - 20 \text{ kPa}}{30 \text{ kPa} - 20 \text{ kPa}} \quad \therefore T_{\text{sat}} = \underline{67.2^\circ\text{C}}$$

**2.22**  $x = \frac{m_{\text{vapor}}}{m_{\text{total}}} = \frac{7 \text{ kg}}{10 \text{ kg} + 7 \text{ kg}} = \underline{0.41}$

**2.23** Quality is determined on a mass basis so we have to use Table C-1 to get the specific volume of each phase in order to calculate the mass of each phase:

$$m_{\text{liquid}} = \frac{V_{\text{liquid}}}{v_f} = \frac{0.03 \text{ m}^3}{0.001036 \text{ m}^3/\text{kg}} = 28.96 \text{ kg}$$

$$m_{\text{vapor}} = \frac{V_{\text{vapor}}}{v_g} = \frac{0.15 \text{ m}^3}{2.361 \text{ m}^3/\text{kg}} = 0.0635 \text{ kg}$$

$$\text{The quality, } x = \frac{m_{\text{vapor}}}{m_{\text{total}}} = \frac{0.0635 \text{ kg}}{28.96 \text{ kg} + 0.0635 \text{ kg}} = 0.0022 = \underline{0.22\%}$$

**2.24** At state 1 the water is a saturated liquid ( $x = 0$ ). The specific volume  $v_f$  at 200 kPa (0.2 MPa) can be found in Table C-2:  $v_f = 0.001061 \text{ m}^3/\text{kg}$ . Then

$$V_1 = mv_f = 4 \text{ kg} (0.001061 \text{ m}^3/\text{kg}) = \underline{0.0042 \text{ m}^3}$$

At state 2 the water is a saturated vapor at 200 kPa. The specific volume  $v_g$  at 200 kPa (0.2 MPa) can be found in Table C-2:  $v_g = 0.8857 \text{ m}^3/\text{kg}$ . Then

$$V_2 = mv_g = 4 \text{ kg} (0.8857 \text{ m}^3/\text{kg}) = \underline{3.543 \text{ m}^3}.$$

**2.25** At state 1 the water is a saturated liquid ( $x = 0$ ). The specific volume  $v_f$  at 400 kPa (0.4 MPa) can be found in Table C-2:  $v_f = 0.001084 \text{ m}^3/\text{kg}$ . So

$$m = \frac{V_1}{v_f} = \frac{0.0004 \text{ m}^3}{0.001084 \text{ m}^3/\text{kg}} = 0.37 \text{ kg}. \text{ (This mass stays constant for the process.)}$$

At state 2 the water is a saturated vapor at 400 kPa. The specific volume  $v_g$  at 400 kPa (0.4 MPa) can be found in Table C-2:  $v_g = 0.4625 \text{ m}^3/\text{kg}$ . So

$$V_2 = mv_g = 0.37 \text{ kg} \times 0.4625 \text{ m}^3/\text{kg} = \underline{0.171 \text{ m}^3}$$

**2.26** We have a fixed mass of 10 kg and a quality  $x = 0.85$  ( $V_{\text{vapor}} = 8.5 \text{ kg}$ ) so the system is a saturated mixture. Table C-2 lists the specific volumes for saturated mixtures.

a) For a pressure of 140 kPa:  $v = v_f + x(v_g - v_f)$

$$\begin{aligned} v &= 0.001051 + 0.85(1.237 - 0.001051) = 1.052 \text{ m}^3/\text{kg} \\ V &= 10 \text{ kg} (1.052 \text{ m}^3/\text{kg}) = 10.52 \text{ m}^3 \\ V_{\text{vapor}} &= 8.5 \text{ kg} (1.237 \text{ m}^3/\text{kg}) = \underline{10.51 \text{ m}^3} \quad \text{and} \quad T = T_{\text{sat}} = \underline{109.3^\circ\text{C}} \end{aligned}$$

b) For a pressure of 200 kPa:  $v = v_f + x(v_g - v_f)$

$$\begin{aligned} v &= 0.001061 + 0.85(0.8857 - 0.001061) = 0.753 \text{ m}^3/\text{kg}. \\ V &= 10 \text{ kg} (0.753 \text{ m}^3/\text{kg}) = 7.53 \text{ m}^3 \\ V_{\text{vapor}} &= 8.5 \text{ kg} (0.8857 \text{ m}^3/\text{kg}) = \underline{7.528 \text{ m}^3} \quad \text{and} \quad T = T_{\text{sat}} = \underline{120.2^\circ\text{C}} \end{aligned}$$

c) For a pressure of 2000 kPa:  $v = v_f + x(v_g - v_f)$

$$\begin{aligned} v &= 0.001177 + 0.85(0.09963 - 0.001177) = 0.0849 \text{ m}^3/\text{kg}. \\ V &= 10 \text{ kg} (0.0849 \text{ m}^3/\text{kg}) = 0.849 \text{ m}^3 \\ V_{\text{vapor}} &= 8.5 \text{ kg} (0.09963 \text{ m}^3/\text{kg}) = \underline{0.847 \text{ m}^3} \quad \text{and} \quad T = T_{\text{sat}} = \underline{212.4^\circ\text{C}} \end{aligned}$$

**2.27** The water is 10 kg of a saturated mixture with a quality of  $0.6 = m_{\text{vapor}}/m_{\text{total}}$ . The properties can be obtained from Table C-1 for  $T = 40^\circ\text{C}$ :

$$v = v_f + x(v_g - v_f) = 0.001008 + 0.6(19.52 - 0.001008) = 11.712 \text{ m}^3/\text{kg}$$

$$V = mv = 10 \text{ kg} \times (11.712 \text{ m}^3/\text{kg}) = 117.12 \text{ m}^3. \quad \therefore V_{\text{liquid}} = 4 \times 0.001008 = \underline{0.00403 \text{ m}^3}$$

$$V_{\text{vapor}} = 6 \text{ kg} \times (19.52 \text{ m}^3/\text{kg}) = \underline{117.12 \text{ m}^3} \quad (\text{The volume is essentially all vapor.})$$

$$P = P_{\text{sat}} = 0.00738 \text{ MPa} = \underline{7.38 \text{ kPa}}$$

**2.28** Table C-2 gives us SI unit saturation information if we know the pressure.

a) For  $P = 0.5 \text{ MPa}$ ,  $T_{\text{sat}} = \frac{143.6 + 158.9}{2} = \underline{151^\circ\text{C}}$

b) For  $P = 1 \text{ MPa}$ ,  $T_{\text{sat}} = \underline{180^\circ\text{C}}$

c) For  $P = 3 \text{ MPa}$ ,  $T_{\text{sat}} = \underline{276^\circ\text{C}}$

**2.29**  $P = 0.0003 \text{ atm} \times 100 \text{ kPa/atm} = 0.03 \text{ kPa}$  or  $0.00003 \text{ MPa}$  which is below the lowest pressure in Table C-2. The saturation temperature would be very near  $0^\circ\text{C}$ .

**2.30** To respond to this problem, please Google “pressure cooker.”

**2.31** We know that the water is a saturated mixture with a volume of  $5 \text{ m}^3$  and a quality of 70%. Table C-1 will give the properties.

a) For  $T = 120^\circ\text{C}$ ,  $P = P_{\text{sat}} = 0.1985 \text{ MPa} = \underline{198.5 \text{ kPa}}$ .

$$m = \frac{V}{v} = \frac{V}{v_f + x(v_g - v_f)} = \frac{5}{0.00106 + 0.7(0.8919 - 0.00106)} = \underline{8.005 \text{ kg}}$$

b) For  $T = 240^\circ\text{C}$ ,  $P = P_{\text{sat}} = 3.344 \text{ MPa} = \underline{3344 \text{ kPa}}$ .

$$m = \frac{V}{v} = \frac{V}{v_f + x(v_g - v_f)} = \frac{5}{0.001229 + 0.7(0.05977 - 0.001229)} = \underline{118.5 \text{ kg}}$$

c) For  $T = 370^\circ\text{C}$ ,  $P = P_{\text{sat}} = \underline{21.03 \text{ MPa}}$ .

$$m = \frac{V}{v} = \frac{V}{v_f + x(v_g - v_f)} = \frac{5}{0.002213 + 0.7(0.004931 - 0.002213)} = \underline{1215 \text{ kg}}$$

**2.32** Table C-1 lists the properties for saturated water in SI units.

For  $T = 50^\circ\text{C}$  we get  $v_f = 0.001012 \text{ m}^3/\text{kg}$  and  $v_g = 12.03 \text{ m}^3/\text{kg}$

Initial volume:  $V_1 = 0.5 \text{ kg} (0.001012 \text{ m}^3/\text{kg}) = \underline{0.0005 \text{ m}^3}$

Final volume:  $V_2 = 0.5 \text{ kg} (12.03 \text{ m}^3/\text{kg}) = \underline{6.015 \text{ m}^3}$  A big change!

**2.33** Since the container is rigid, the volume and specific volume stay constant. Table C-1 or C-2 gives the properties at the critical point:  $v = 0.003155 \text{ m}^3/\text{kg}$ .

a) Table C-2 gives properties for saturated water. At 2 MPa

$$x = \frac{v - v_f}{v_g - v_f} = \frac{0.003155 - 0.001177}{0.09963 - 0.001177} = 0.0201 = \underline{2.01\%}$$

b) Table C-2 gives properties for saturated water. At 1.2 MPa

$$x = \frac{v - v_f}{v_g - v_f} = \frac{0.003155 - 0.001139}{0.1633 - 0.001139} = 0.0124 = \underline{1.24\%}$$

c) Table C-2 gives properties for saturated water. At 0.4 MPa

$$x = \frac{v - v_f}{v_g - v_f} = \frac{0.003155 - 0.001084}{0.4625 - 0.001084} = 0.00449 = \underline{0.449\%}$$

**2.34** The water is initially at 200 kPa and  $x = 0.1$ . We can calculate the constant specific volume of the rigid container using the information from Table C-2:

$$v = v_f + x(v_g - v_f) = 0.001061 + 0.1(0.8857 - 0.001061) = 0.0895 \text{ m}^3/\text{kg}$$

a) At 140°C from Table C-1:  $P = \underline{361.3 \text{ kPa}}$

$$x = \frac{v - v_f}{v_g - v_f} = \frac{0.0895 - 0.00108}{0.5089 - 0.00108} = 0.174 \text{ or } \underline{17.4\%}$$

b) At 180°C from Table C-1:  $P = \underline{1002 \text{ kPa}}$

$$x = \frac{v - v_f}{v_g - v_f} = \frac{0.0895 - 0.001127}{0.1941 - 0.001127} = 0.458 \text{ or } \underline{45.8\%}$$

c) At 210°C from Table C-1:  $P = 1906 \text{ kPa}$

$$x = \frac{v - v_f}{v_g - v_f} = \frac{0.0895 - 0.001173}{0.1044 - 0.001173} = 0.856 \text{ or } \underline{85.6\%}$$

**2.35** At state 1 the water is a subcooled liquid at 25°C, so an accurate estimate of the specific volume is to use  $v_f$  at 25°C. From Table C-1,  $v_1 = 0.001003 \text{ m}^3/\text{kg}$ . The specific volume at 120°C from Table C-1 is  $v_f = 0.00106 \text{ m}^3/\text{kg}$ . Hence,

$$\Delta V = m(v_2 - v_1) = 4 \times (0.00106 - 0.001003) = \underline{0.000228 \text{ m}^3}. \text{ Very little change.}$$

**2.36 State 1:**  $m = 2 \text{ kg}$ ,  $T_1 = 20^\circ\text{C}$ , and  $P_1 = 5 \text{ MPa}$ . This is a subcooled liquid.

**State 2:**  $m = 2 \text{ kg}$ ,  $T_2 = 200^\circ\text{C}$ , and  $P_2 = P_1 = 5 \text{ MPa}$ . At this temperature the water remains a subcooled liquid since  $P < P_{\text{sat}} = 1.55 \text{ MPa}$ .

i) Using Table C-4 for the specific volume at state 1,  $v_1 = 0.001 \text{ m}^3/\text{kg}$ . For state 2,  $v_2 = 0.001153 \text{ m}^3/\text{kg}$ .

$$\Delta V = 2(0.001153 - 0.001) = \underline{0.000306 \text{ m}^3}$$

ii) Use Table C-1 to get the specific volumes using the  $v_f$  values:

$$v_1 = 0.001002 \text{ m}^3/\text{kg}, \quad v_2 = 0.001156 \text{ m}^3/\text{kg}$$

$$\Delta V = 2(0.001156 - 0.001002) = \underline{0.000308 \text{ m}^3} \text{ (essentially the same answer)}$$

Conclusion: Table C-1 can be used to find  $v$  for compressed liquids. Simply ignore the pressure.



**2.37** At state 1 the quality is zero and the pressure is 200 kPa or 0.2 MPa. Use Table C-2 to find  $v_1 = v_f = 0.001061 \text{ m}^3/\text{kg}$ . At state 2 the pressure is 2 MPa and the temperature is 400°C. Here the water is a superheated vapor. Use Table C-3 to get the specific volume:  $v_2 = 0.1512 \text{ m}^3/\text{kg}$ . Then

$$\Delta V = 2 (0.1512 - 0.001061) = \underline{0.300 \text{ m}^3}$$

**2.38** At state 1 the water is a saturated mixture with a temperature of 130°C and a quality of 0.4. The pressure is the saturation pressure at 130°C which, from Table C-1, is 0.2701 MPa or 270.1 kPa. From this table we get the specific volumes for a saturated liquid  $v_f$  and a saturated vapor  $v_g$  to calculate

$$v = v_f + x(v_g - v_f) = 0.00107 + 0.4(0.6685 - 0.00107) = 0.268 \text{ m}^3/\text{kg}$$

$$V_{\text{total}} = 10 \times 0.268 = \underline{2.68 \text{ m}^3}$$

The volume of liquid is  $V_f = 0.6 \times 10 \times 0.00107 \text{ m}^3/\text{kg} = \underline{0.0064 \text{ m}^3}$

**2.39** The specific volume of the water is  $v = V/m = \frac{1.9 \text{ m}^3}{4.6 \text{ kg}} = 0.413 \text{ m}^3/\text{kg}$

i) For  $v = 0.413 \text{ m}^3/\text{kg}$  and  $P = 350 \text{ kPa}$ , use Table C-2 to find that  $v_f < 0.413 < v_g$ . The water is a saturated mixture.

ii) For  $v = 0.413 \text{ m}^3/\text{kg}$  and  $P = 450 \text{ kPa}$ , use Table C-2 to find that  $0.413 > v_g$  ( $= 0.389 \text{ m}^3/\text{kg}$ ). The water is a superheated vapor.

iii) For  $v = 0.413 \text{ m}^3/\text{kg}$  and  $P = 700 \text{ kPa}$ , use Table C-2 to find that  $v > v_g$ . The water is a superheated vapor.

**2.40** The problem states that the water is initially a “saturated water vapor” so  $x = 1$ . Knowing that  $T = 200^\circ\text{C}$  we use table C-1 to get  $P_1 = P_{\text{sat}} = \underline{1554 \text{ kPa}}$ . The specific volume is  $v = v_g = 0.1274 \text{ m}^3/\text{kg}$ .

a) If the temperature stays constant and the volume increases by 50%,  $v_1 = 1.5v = 1.5 \times 0.1274 \text{ m}^3/\text{kg} = 0.1911 \text{ m}^3/\text{kg}$  which is in the superheat range being greater than  $v_g$ . We can use Table C-3 to get the properties but this would require interpolating between pressures of 1 MPa and 1.2 MPa. Use the IRC Calculator:  $P_2 = \underline{1070 \text{ kPa}}$ .

b) If the temperature stays constant and we increase the volume by 100%  $v_1 = 2v = 2 \times 0.1274 \text{ m}^3/\text{kg} = 0.2548 \text{ m}^3/\text{kg}$  which is in the superheat range being greater than  $v_g$ . We can use Table C-3 to get the properties but this would require interpolating between pressures of 0.8 MPa and 1 MPa. Use the IRC Calculator:  $P_2 = \underline{818 \text{ kPa}}$ .

c) If the temperature stays constant and we increase the volume by 200%  $v_1 = 3v = 3 \times 0.1274 \text{ m}^3/\text{kg} = 0.3822 \text{ m}^3/\text{kg}$  which is in the superheat range being greater than  $v_g$ . We can use Table C-3 to get the properties but this would require interpolating between pressures of 0.4 MPa and 0.6 MPa. Use the IRC Calculator:  $P_2 = \underline{554 \text{ kPa}}$ .

**2.41** At 300 kPa and 200°C the water is superheated ( $P < P_{\text{sat at } 200^\circ}$ ). From Table C-3 we get  $v = 1.0803 \text{ m}^3/\text{kg}$ :

$$m = V/v = 0.27 \text{ m}^3 / 1.0803 \text{ m}^3/\text{kg} = \underline{0.25 \text{ kg}}$$

**2.42 a)** For  $P = 5 \text{ MPa}$  and  $T = -5^\circ\text{C}$  the water is solid ice. Table C-5 gives the specific volume for ice to be  $1.09 \times 10^{-3} \text{ m}^3/\text{kg}$ :

$$V = mv = 8 \text{ kg} \times 0.00109 \text{ m}^3/\text{kg} = \underline{0.00872 \text{ m}^3}$$

**b)** For  $P = 5 \text{ MPa}$  and  $T = 20^\circ\text{C}$  the water is a subcooled liquid. Table C-4 gives the specific volume for the water to be  $0.001 \text{ m}^3/\text{kg}$ :

$$V = mv = 8 \text{ kg} \times 0.001 \text{ m}^3/\text{kg} = \underline{0.008 \text{ m}^3}$$

**c)** For  $P = 5 \text{ MPa}$  and  $T = 400^\circ\text{C}$  the water is a superheated vapor. Table C-3 gives the specific volume for the vapor to be  $0.05781 \text{ m}^3/\text{kg}$ :

$$V = mv = 8 \text{ kg} \times 0.05781 \text{ m}^3/\text{kg} = \underline{0.4625 \text{ m}^3}$$

**d)** For  $P = 5 \text{ MPa}$  and  $T = 800^\circ\text{C}$  the water is a superheated vapor. Table C-3 gives the specific volume for the vapor to be  $0.09811 \text{ m}^3/\text{kg}$ :

$$V = mv = 8 \text{ kg} \times 0.09811 \text{ m}^3/\text{kg} = \underline{0.7849 \text{ m}^3}$$

**2.43** The weight of the piston is  $W = mg = 160 \text{ kg} (9.81 \text{ m/s}^2) = 1569.6 \text{ N}$ .  
The pressure caused by the weight of the piston:

$$P_{\text{piston}} = W/A_{\text{piston}} = \frac{1569.6 \text{ N}}{\pi \times 0.1^2 \text{ m}^2} = 49\,960 \text{ Pa or } 50 \text{ kPa}$$

The initial pressure is

$$P_1 = P_{\text{piston}} + P_{\text{atm}} = 50 \text{ kPa} + 100 \text{ kPa} = 150 \text{ kPa}.$$

At the initial state, the pressure is 150 kPa and  $x = 1$ . The temperature is the saturation temperature at 150 kPa, which from Table C-2 is  $111^\circ\text{C}$ , by interpolation. Also by interpolation,  $v_1 = v_g = 1.107 \text{ m}^3/\text{kg}$ . Then  $V_1 = 0.02 \text{ kg} \times 1.107 \text{ m}^3/\text{kg} = \underline{0.022 \text{ m}^3}$ .

**a)** To compress the spring 6 cm, the additional pressure is

$$P = \frac{Kx}{A} = \frac{(60\,000 \text{ N/m})(0.06 \text{ m})}{\pi \times 0.1^2 \text{ m}^2} = 115\,000 \text{ N/m}^2 = 115 \text{ kPa}$$

So,  $P_2 = 150 \text{ kPa} + 115 \text{ kPa} = 265 \text{ kPa}$ . The volume is

$$V_2 = V + \Delta V = 0.022 \text{ m}^3 + 0.06 \text{ m} \times \pi(0.1 \text{ m})^2 = 0.024 \text{ m}^3$$

The specific volume is then  $v_2 = 0.024 \text{ m}^3 / 0.02 \text{ kg} = 1.2 \text{ m}^3/\text{kg}$ . Using the IRC calculator with  $P_2 = 265 \text{ kPa}$ , the temperature is  $T_2 = \underline{418^\circ\text{C}}$ .

b) To compress the spring 10 cm, the additional pressure is

$$P = \frac{Kx}{A} = \frac{(60\,000 \text{ N/m})(0.1 \text{ m})}{\pi \times 0.1^2 \text{ m}^2} = 191\,000 \text{ N/m}^2 = 191 \text{ kPa}$$

So,  $P_2 = 150 \text{ kPa} + 191 \text{ kPa} = 341 \text{ kPa}$ . The volume is

$$V_2 = V + \Delta V = 0.022 \text{ m}^3 + 0.1 \text{ m} \times \pi(0.1 \text{ m})^2 = 0.025 \text{ m}^3.$$

The specific volume is then  $v_2 = 0.025 \text{ m}^3/0.02 \text{ kg} = 1.25 \text{ m}^3/\text{kg}$ . Using the IRC calculator with  $P_2 = 341 \text{ kPa}$ , the temperature is  $T_2 = \underline{652^\circ\text{C}}$ .

c) To compress the spring 15 cm, the additional pressure is

$$P = \frac{Kx}{A} = \frac{(60\,000 \text{ N/m})(0.15 \text{ m})}{\pi \times 0.1^2 \text{ m}^2} = 286\,000 \text{ N/m}^2 = 286 \text{ kPa}$$

So,  $P_2 = 150 \text{ kPa} + 286 \text{ kPa} = 436 \text{ kPa}$ . The volume is

$$V_2 = V + \Delta V = 0.022 \text{ m}^3 + 0.15 \text{ m} \times \pi(0.1 \text{ m})^2 = 0.027 \text{ m}^3$$

The specific volume is then  $v_2 = 0.027 \text{ m}^3/0.02 \text{ kg} = 1.35 \text{ m}^3/\text{kg}$ . Using the IRC Calculator with  $P_2 = 436 \text{ kPa}$ , the temperature is  $T_2 = \underline{1010^\circ\text{C}}$ .

**2.44** The weight of the piston is  $W = mg = 160 \text{ kg} \times 9.81 \text{ m/s}^2 = 1570 \text{ N}$ .  
The pressure caused by the weight of the piston is

$$P = \frac{W}{A} = \frac{1570 \text{ N}}{\pi \times 0.1^2 \text{ m}^2} = 49\,970 \text{ N/m}^2 = 50 \text{ kPa}$$

The initial pressure  $P_1 = P_{\text{piston}} + P_{\text{atm}} = 50 \text{ kPa} + 100 \text{ kPa} = 150 \text{ kPa}$ .

For a pressure of 150 kPa and  $x = 0.8$ , we can calculate the specific volume using the data in Table C-2 between 0.14 MPa and 0.16 MPa. By interpolation:

$$v_1 = 0.001052 + 0.8(1.164 - 0.001052) = 0.931 \text{ m}^3/\text{kg}$$

Also by interpolation the saturation temperature is  $111^\circ\text{C}$ .

For the final state, the temperature is  $800^\circ\text{C}$  which means the final state is probably a superheated vapor. The only thing that stays constant in this problem is the mass. We have to balance the position of the piston, the pressure, and the temperature to find the final state. This is done by trial and error. The initial volume in the cylinder can be calculated from state 1:

$$V_1 = 0.931 \text{ m}^3/\text{kg} \times 0.02 \text{ kg} = 0.0186 \text{ m}^3$$

For the final state  $T_2 = 800^\circ\text{C}$  and

$$P_2 = 150 \text{ kPa} + \frac{(60 \text{ kN/m})x}{\pi \times 0.1^2 \text{ m}^2}, \quad v_2 = \frac{V}{m} = \frac{0.0186 \text{ m}^3 + (\pi \times 0.1^2 x) \text{ m}^3}{0.02 \text{ kg}}$$

We must choose a value of the piston displacement  $x$  so that all three properties match in the steam tables. This occurs for  $x = 15 \text{ cm}$  and  $P_2 = \underline{424 \text{ kPa}}$ . The quickest and easiest way to solve this is to use the IRC Calculator.

**2.45** From Problem 2.43,  $P_{\text{initial}} = 150 \text{ kPa}$ ,  $x = 1$ ,  $T_1 = 111.3^\circ\text{C}$ ,  $v_1 = 1.107 \text{ m}^3/\text{kg}$  and  $V_1 = 0.022 \text{ m}^3$ . The piston must rise 2 cm to reach the piston. This will be at constant pressure:

$$P_2 = 150 \text{ kPa}, \quad V_2 = 0.022 \text{ m}^3 + [0.02 \times \pi \times (0.1)^2] \text{ m}^3 = 0.0226 \text{ m}^3$$

$$v_2 = \frac{0.0226 \text{ m}^3}{0.02 \text{ kg}} = 1.13 \text{ m}^3/\text{kg}$$

Using the IRC Calculator with  $P_2 = 150 \text{ kPa}$  and  $v_2 = 1.13 \text{ m}^3/\text{kg}$  we get  $T_2 = 111^\circ\text{C}$  and  $x_2 = 0.975$ , a saturated mixture.

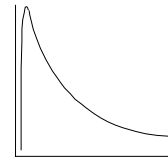
At the final state 3, the spring is compressed 6 cm. Then

$$V_3 = 0.0226 \text{ m}^3 + 0.06 \times \pi \times 0.1^2 = 0.0245 \text{ m}^3, \quad v_3 = \frac{0.0245 \text{ m}^3}{0.02 \text{ kg}} = 1.225 \text{ m}^3/\text{kg}$$

$$P_3 = 150 \text{ kPa} + 115 \text{ kPa} = 265 \text{ kPa} \quad (\text{from Problem 2.43})$$

For  $P_3 = 265 \text{ kPa}$  and  $v_3 = 1.225 \text{ m}^3/\text{kg}$  we use the IRC Calculator to get  $T_3 = 432^\circ\text{C}$ , a superheated vapor.

**2.46** Draw the diagrams to scale. Not many points are needed to observe the general shape. Each diagram will resemble this sketch:



**2.47** Use Table C-2 to find the properties for this saturated mixture at 1.6 MPa:

$$\begin{aligned} T &= T_{\text{sat}} = 201.4^\circ\text{C} \\ u_f &= 856.9 \text{ kJ/kg} \\ u_g &= 2596 \text{ kJ/kg} \\ h_f &= 858.8 \text{ kJ/kg} \\ h_g &= 2794 \text{ kJ/kg} \\ u &= 856.9 + 0.4(2596 - 856.9) = \underline{1553 \text{ kJ/kg}} \\ h &= 858.8 + 0.4(2794 - 858.8) = \underline{1633 \text{ kJ/kg}} \end{aligned}$$

**2.48** The steam is at 1.86 MPa and  $420^\circ\text{C}$ .

i) Using Table C-3 we must double interpolate for both pressure and temperature.

	<b><math>P = 1.8 \text{ MPa}</math></b>	<b><math>P = 2 \text{ MPa}</math></b>
<b><math>T = 400^\circ\text{C}</math></b>	$h = 3250.9$	$h = 3247.6$
<b><math>T = 500^\circ\text{C}</math></b>	$h = 3469.8$	$h = 3467.6$

$$\therefore h_{1.86\text{MPa}, 420^\circ\text{C}} = \underline{3294 \text{ kJ/kg}}$$

ii) For  $P = 1860 \text{ kPa}$  and  $T = 420^\circ\text{C}$ , use the IRC calculator:

$$h = \underline{3290 \text{ kJ/kg}}, \quad u = 2980 \text{ kJ/kg}, \quad \text{and} \quad v = 0.168 \text{ m}^3/\text{kg}$$

iii) Using values from Part (ii)  $h = 2980 + 1860 \times 0.168 = \underline{3290 \text{ kJ/kg}}$  (The numbers are to 3 significant digits, so the answer is expressed with 3 significant digits.)

All the answers are acceptable. The fourth digit in Part (i) undoubtedly is meaningless. Significant digits are always lost when using straight-line interpolations.

**2.49** At state 1 the water is saturated vapor ( $x = 1$ ) at  $150^\circ\text{C}$ . At state 2 the water is saturated liquid ( $x = 0$ ).

a) Use Table C-1 for the properties. The saturation pressure at  $150^\circ\text{C}$  is 476.8 kPa and:

$$v_f = 0.001090 \text{ m}^3/\text{kg}, \quad u_f = 631.7 \text{ kJ/kg}, \quad h_f = 632.2 \text{ kJ/kg}$$

$$v_g = 0.3928 \text{ m}^3/\text{kg}, \quad u_g = 2559.5 \text{ kJ/kg}, \quad h_g = 2746.4 \text{ kJ/kg}$$

$$\Delta V = 5 (0.3928 - 0.001090) = 1.958 \text{ m}^3$$

$$\Delta U = 5 (2559.5 - 631.7) = 9693 \text{ kJ}$$

$$\Delta H = 5 (2746.4 - 632.2) = 10571 \text{ kJ}$$

$$\Delta H = \Delta U + P\Delta V$$

$$= 9693 + (475.8 \text{ kPa}) (1.958 \text{ m}^3) = \underline{10\,620 \text{ kJ}}$$

b) Use the IRC Calculator for the properties:  $P_{\text{sat}} = 477 \text{ kPa}$  and :

$$v_f = 0.001090 \text{ m}^3/\text{kg}, \quad u_f = 632 \text{ kJ/kg}, \quad h_f = 632.4 \text{ kJ/kg}$$

$$v_g = 0.390 \text{ m}^3/\text{kg}, \quad u_g = 2560 \text{ kJ/kg}, \quad h_g = 2746 \text{ kJ/kg}$$

$$\Delta V = 5 (0.390 - 0.001090) = 1.9445 \text{ m}^3$$

$$\Delta U = 5 (2560 - 632) = 9640 \text{ kJ}$$

$$\Delta H = 5 (2746 - 632.4) = 10\,570 \text{ kJ}$$

$$\Delta H = \Delta U + P\Delta V$$

$$= 9640 + (477 \text{ kPa}) (1.9445 \text{ m}^3) = \underline{10\,600 \text{ kJ}}$$

**2.50** State 1 is a saturated vapor ( $x = 1$ ) at  $200^\circ\text{C}$ . State 2 is a superheated vapor at 2 MPa and  $600^\circ\text{C}$ .

a) The properties for state 1 come from Table C-1:

$$v_1 = v_g = 0.1274 \text{ m}^3/\text{kg}, \quad h_1 = h_g = 2793.2 \text{ kJ/kg}$$

The properties for state 2 come from Table C-3:

$$v_2 = 0.1996 \text{ m}^3/\text{kg}, \quad h_2 = 3690.1 \text{ kJ/kg}$$

$$\Delta v = 0.1996 - 0.1274 = \underline{0.0722 \text{ m}^3/\text{kg}}$$

$$\Delta h = 3690.1 - 2793.2 = \underline{896.9 \text{ kJ/kg}}$$

b) Use the IRC Calculator:

$$v_1 = 0.127 \text{ m}^3/\text{kg}, \quad h_1 = 2790 \text{ kJ/kg}$$

$$v_2 = 0.2 \text{ m}^3/\text{kg}, \quad h_2 = 3690 \text{ kJ/kg}$$

$$\Delta v = 0.2 - 0.127 = \underline{0.073 \text{ m}^3/\text{kg}}$$

$$\Delta h = 3690 - 2790 = \underline{900 \text{ kJ/kg}}$$

**2.51** The pressure stays constant at 200 kPa:

**State 1:**  $T_1 = 20^\circ\text{C}$ ,  $P_1 = 200 \text{ kPa}$  (treat this as a saturated liquid at  $20^\circ\text{C}$ )

**State 2:**  $T_2 = 400^\circ\text{C}$ ,  $P_2 = P_1 = 200 \text{ kPa}$  or  $0.2 \text{ MPa}$  (superheated vapor)

a) The properties for state 1 are from Table C-1 at 20°C:

$$v_1 = v_f = 0.001002 \text{ m}^3/\text{kg}, \quad u_1 = u_f = 83.9 \text{ kJ/kg}, \quad h_1 = h_f = 83.9 \text{ kJ/kg}$$

The properties for state 2 are from Table C-3 at 400°C:

$$\begin{aligned} v_2 &= 1.5493 \text{ m}^3/\text{kg}, \quad u_2 = 2966.7 \text{ kJ/kg}, \quad h_2 = 3276.6 \text{ kJ/kg} \\ \Delta\rho &= 0.001002^{-1} - 1.5493^{-1} = \underline{997 \text{ kg/m}^3} \\ \Delta U &= 4 \times (2966.7 - 83.9) = \underline{11\,530 \text{ kJ}} \\ \Delta H &= 4 \times (3276.6 - 83.9) = \underline{12\,770 \text{ kJ}} \end{aligned}$$

b) Use the IRC Calculator:

$$\begin{aligned} \text{At } 20^\circ\text{C: } & v_1 = v_f = 0.001 \text{ m}^3/\text{kg}, \quad u_1 = u_f = 83.9 \text{ kJ/kg}, \quad h_1 = h_f = 84.1 \text{ kJ/kg} \\ \text{At } 400^\circ\text{C: } & v_2 = 1.55 \text{ m}^3/\text{kg}, \quad u_2 = 2970 \text{ kJ/kg}, \quad h_2 = 3280 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \Delta\rho &= 0.001^{-1} - 1.55^{-1} = \underline{999 \text{ kg/m}^3} \\ \Delta U &= 4 \times (2970 - 83.9) = \underline{11\,500 \text{ kJ}} \quad (\text{the Calculator uses only 3 significant digits}) \\ \Delta H &= 4 \times (3280 - 84.1) = \underline{12\,800 \text{ kJ}} \end{aligned}$$

**2.52 State 1:**  $m = 20 \text{ kg}$ ,  $T_1 = 300^\circ\text{C}$ ,  $P_1 = 0.6 \text{ MPa}$  superheated

**State 2:**  $T_2 = 400^\circ\text{C}$ ,  $P_2 = P_1 = 0.6 \text{ MPa}$  superheated

a) Use Table C-3 for the enthalpies:

$$h_1 = 3061.6 \text{ kJ/kg}, \quad h_2 = 3270.3 \text{ kJ/kg}, \quad \therefore \Delta H = 20 \times (3270.3 - 3061.6) = \underline{4174 \text{ kJ}}$$

b) Use the IRC Calculator for the enthalpies:

$$h_1 = 3060 \text{ kJ/kg}, \quad h_2 = 3270 \text{ kJ/kg}, \quad \therefore \Delta H = 20 \times (3270 - 3060) = \underline{4200 \text{ kJ}}$$

**2.53** You must determine the specific properties in this problem since the mass of the system is not known.

**State 1:**  $T_1 = 40^\circ\text{C}$ ,  $P_1 = 3.5 \text{ MPa}$  subcooled liquid

**State 2:**  $T_2 = 260^\circ\text{C}$ ,  $P_2 = P_1 = 3.5 \text{ MPa}$  superheated vapor

a) Use Table C-4 for the properties at state 1:

$$u_1 = 166.4 \text{ kJ/kg}, \quad h_1 = 169.2 \text{ kJ/kg}$$

Use Table C-3 for the properties at state 2:

$$u_2 = 2682 \text{ kJ/kg}, \quad h_2 = 2860 \text{ kJ/kg}$$

$$\therefore \Delta u = 2682 - 166.4 = \underline{2516 \text{ kJ/kg}}$$

$$\therefore \Delta h = 2860 - 169.2 = \underline{2691 \text{ kJ/kg}}$$

b) Use the IRC Calculator:

$$\begin{aligned} u_1 &= 167 \text{ kJ/kg}, \quad h_1 = 170 \text{ kJ/kg}, \quad u_2 = 2685 \text{ kJ/kg}, \quad h_2 = 2864 \text{ kJ/kg} \\ \therefore \Delta u &= 2685 - 167 = \underline{2518 \text{ kJ/kg}}, \quad \therefore \Delta h = 2864 - 170 = \underline{2694 \text{ kJ/kg}} \end{aligned}$$

**2.54** At state 1 the water is solid ice at 100 kPa and  $-20^{\circ}\text{C}$ . The specific internal energy can be obtained from Table C-5:

$$u_1 = -374 \text{ kJ/kg}$$

At state 2 the water is a subcooled liquid at 100 kPa and  $20^{\circ}\text{C}$ . The specific internal energy can be obtained from Table C-1 for  $T_2 = 20^{\circ}\text{C}$ :

$$u_2 = u_f = 83.9 \text{ kJ/kg}$$

$$\therefore \Delta U = m(u_g - u_i) = 10 [83.9 - (-374)] = \underline{4580 \text{ kJ}}$$

**2.55** The water is undergoing sublimation from solid ice at  $-20^{\circ}\text{C}$  to a saturated vapor at  $-20^{\circ}\text{C}$ . Table C-5 gives the properties for these states:

$$\Delta U = m(u_g - u_i) = 4 [2348 - (-374)] = \underline{10\,890 \text{ kJ}}$$

**2.56** We are given  $V = 0.05 \text{ m}^3$  and  $m = 50 \text{ kg}$  so

$$v = \frac{0.05 \text{ m}^3}{50 \text{ kg}} = 0.001 \text{ m}^3/\text{kg}$$

a) For  $P = 2.5 \text{ MPa}$  or  $2500 \text{ kPa}$ , from Table D-2, we find the specific volume for a saturated liquid and a saturated vapor.

$$v_f = 0.0010562 \text{ m}^3/\text{kg}, \quad v_g = 0.0069 \text{ m}^3/\text{kg}$$

Since  $v$  is less than  $v_f$ , the R134a is a subcooled liquid.

b) For  $P = 240 \text{ kPa}$  we use Table D-2 to obtain the saturation specific volumes.

$$v_f = 0.0007618 \text{ m}^3/\text{kg}, \quad v_g = 0.0834 \text{ m}^3/\text{kg}$$

Again, since  $v$  is greater than  $v_f$  but less than  $v_g$ , the R134a is a saturated mixture with

$$x = \frac{0.001 - 0.0007618}{0.0834 - 0.0007618} = 0.00288 \quad \text{or} \quad 0.288\%$$

**2.57** The specific volume of the refrigerant is  $v = \frac{0.27 \text{ m}^3}{45 \text{ kg}} = 0.006 \text{ m}^3/\text{kg}$

Use Table D-1 for  $T = -30^{\circ}\text{C}$ :

$$v_f = 0.0007203 \text{ m}^3/\text{kg}, \quad v_g = 0.2251 \text{ m}^3/\text{kg}$$

Since  $v_f < v < v_g$  the R134a is a saturated mixture with

$$x = \frac{0.006 - 0.00072}{0.2251 - 0.00072} = 0.0235 \quad \text{or} \quad 2.35\%$$

**2.58** At 200 kPa the saturation temperature of R134a is  $-12^{\circ}\text{C}$  so the refrigerant is a subcooled liquid. Using Table D-1, the saturated liquid properties at  $-12^{\circ}\text{C}$  are

$$v_1 = v_f = 0.0007498 \text{ m}^3/\text{kg}, \quad u_1 = u_f = 34.25 \text{ kJ/kg}, \quad h_1 = h_f = 34.39 \text{ kJ/kg}$$

At state 2 the pressure remains constant at 200 kPa and  $T_2 = 60^{\circ}\text{C}$ . The refrigerant is now a superheated vapor and we use Table D-3:

$$v_2 = 0.132 \text{ m}^3/\text{kg}, \quad u_2 = 278.1 \text{ kJ/kg}, \quad h_2 = 304.5 \text{ kJ/kg}.$$

- i)  $\Delta V = 100 \text{ kg} \times (0.132 - 0.0007498) = \underline{13.13 \text{ m}^3}$
- ii)  $\Delta U = 100 \text{ kg} \times (278.1 - 34.25) = \underline{24\,380 \text{ kJ}}$
- iii)  $\Delta H = 100 \text{ kg} \times (304.5 - 34.39) = \underline{27\,010 \text{ kJ}}$

**2.59 State 1:**  $T_1 = 30^{\circ}\text{C}$  and  $x_1 = 0$ . See Table D-1:

$$P_1 = P_{\text{sat}} = 770.06 \text{ kPa}, \quad h_1 = h_f = 91.49 \text{ kJ/kg}$$

**State 2:**  $P_2 = 70 \text{ kPa}$  and  $h_2 = h_1 = 91.49 \text{ kJ/kg}$ .

We can get the enthalpy data from Table D-2 at 70 kPa:  $h_f = 6.965 \text{ kJ/kg}$ ,  $h_g = 226.5 \text{ kJ/kg}$ . Since  $h_2$  is between these two values, the state is a saturated mixture. The temperature at state 2 is the saturation temperature of  $\underline{-34.1^{\circ}\text{C}}$  (very cold) and

$$h = h_f + xh_{fg}. \quad 91.49 = 6.965 + x(219.53). \quad \therefore x = 0.387 \text{ or } \underline{38.7\%}$$

**2.60** The working fluid is ammonia.

**State 1:**  $T_1 = -40^{\circ}\text{C}$  and  $x = 0.95$ . From Table E-1:  $h_f = 0.0 \text{ kJ/kg}$ ,  $h_{fg} = 1389 \text{ kJ/kg}$   
 $\therefore h_1 = 0.0 + 0.95 \times 1389 = 1320 \text{ kJ/kg}$

**State 2:**  $P_2 = 400 \text{ kPa}$ ,  $T_2 = 40^{\circ}\text{C}$ . Use Table E-2 for superheat:  $h_2 = 1544.9 \text{ kJ/kg}$ .  
 $\therefore \Delta h = 1544.9 - 1320 = \underline{225 \text{ kJ/kg}}$

**2.61** We know the mass, the pressure and the temperature of the air. Use the ideal gas law to determine the specific volume. Use Table B-2 to get the gas constant for air:

$$v_1 = \frac{RT_1}{P_1} = \frac{0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \times 293 \text{ K}}{120 \text{ kPa}} = 0.7 \text{ m}^3/\text{kg}. \quad \therefore V_1 = mv_1 = 0.1 \times 0.7 = \underline{0.07 \text{ m}^3}$$

At the final state  $T_2 = 35^{\circ}\text{C}$  or  $308 \text{ K}$

$$v = \frac{RT}{P} = \frac{0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \times 308 \text{ K}}{120 \text{ kPa}} = 0.737 \text{ m}^3/\text{kg}. \quad \therefore V_2 = mv_2 = 0.1 \times 0.737 = \underline{0.0737 \text{ m}^3}$$

In the above, the units convert as  $\frac{\text{kJ}}{\text{kg} \cdot \text{K}} \cdot \frac{\text{K}}{\text{kPa}} = \frac{\text{kN} \cdot \text{m}}{\text{kg} \cdot \text{K}} \cdot \frac{\text{K}}{\text{kN/m}^2} = \frac{\text{m}^3}{\text{kg}}$ .



**2.62**  $V = 4/3 \times \pi r^3 = (4/3) \times \pi (0.3)^3 = 0.11304 \text{ m}^3$ ,  $T = 22^\circ\text{C} = 295\text{K}$ ,  $P = 100 \text{ kPa}$

$$v = \frac{RT}{P} = \frac{2.0785 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \times 295\text{K}}{100 \text{ kPa}} = 6.131 \frac{\text{m}^3}{\text{kg}}, \quad m = \frac{V}{v} = \frac{0.11304 \text{ m}^3}{6.131 \text{ m}^3/\text{kg}} = 0.0184 \text{ kg}$$

At 1500 m the pressure is  $0.836P_0 = 0.836 \times 100 \text{ kPa} = 83.6 \text{ kPa}$  from Table B-1.  
We assume that the temperature does not change:

$$v_2 = \frac{RT}{P_2} = \frac{2.0785 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \times 295\text{K}}{83.6 \text{ kPa}} = 7.33 \text{ m}^3/\text{kg}$$

$$V = mv = 0.0184 \times 7.33 = 0.135 \text{ m}^3$$

Since  $V = \frac{4}{3} \pi r^3 = 0.135 \text{ m}^3$ ,  $r = 0.318 \text{ m}$  and  $d = \underline{0.636 \text{ m}}$ .

**2.63** For carbon dioxide, Table B-2 gives  $R_{\text{CO}_2} = 0.1889 \text{ kJ/kg}\cdot\text{K}$ . For  $P = 1 \text{ kPa}$  and  $T = -60^\circ\text{C}$  or  $213 \text{ K}$ . Then

$$v = \frac{RT}{P} = \frac{0.1889 \times 213 \text{ K}}{1} = \underline{40.24 \text{ m}^3/\text{kg}} \quad (\text{See Problem 2.61 for units})$$

**2.64** The container has a constant volume of  $5 \text{ m}^3$  and an initial temperature of  $300 \text{ K}$ . Use the ideal gas law to find the final mass. The final pressure is  $500 \text{ kPa}$ :

$$m_2 = \frac{P_2 V}{RT} = \frac{500 \times 5}{0.287 \times 300} = 29.04 \text{ kg} \quad (\text{See Problem 2.61 for units.})$$

$$\Delta m = 29.04 - 0.2 = \underline{28.8 \text{ kg}}$$

**2.65** Initially,  $m = 5 \text{ kg}$ ,  $P_1 = 100 \text{ kPa}$ , and  $T_1 = 27^\circ\text{C}$  or  $300 \text{ K}$ :

$$V_1 = \frac{mRT_1}{P_1} = \frac{5 \text{ kg} \times 0.287 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \times 300 \text{ K}}{100 \text{ kPa}} = 4.305 \text{ m}^3$$

The final volume  $V_2 = V_1/4 = 4.305/4 = 1.076 \text{ m}^3$ . With  $P_2 = 280 \text{ kPa}$ ,

$$T_2 = \frac{P_2 V_2}{mR} = \frac{280 \text{ kPa} \times 1.076 \text{ m}^3}{5 \text{ kg} \times 0.287 \text{ kJ/kg}\cdot\text{K}} = \underline{210 \text{ K}}$$

**2.66** The gas is unknown so the gas constant is unknown.

$$v = \frac{4}{2} = 2 \text{ m}^3/\text{kg}, \quad R = \frac{Pv}{T} = \frac{400 \times 2}{385} = 2.077 \text{ kJ/kg}\cdot\text{K}$$

From Table B-2 we see that the gas is helium.

**2.67** Convert the temperature to 293 K:

$$m = \frac{PV}{RT} = \frac{100 \times (2 \times 10^6)}{0.287 \times 293} = 2.38 \times 10^6 \text{ kg}$$

$$W = mg = 2.38 \times 10^6 \text{ kg} (9.81 \text{ m/s}^2) = 2.33 \times 10^7 \text{ N or } \underline{23.3 \text{ MN}}$$

**2.68** Given:  $V = 10 \text{ m}^3$ :

i)  $v = \frac{RT}{P} = \frac{0.287 \times 473}{200} = \underline{0.679 \text{ m}^3/\text{kg}}, \quad \rho = \frac{1}{v} = \frac{1}{0.679} = \underline{1.473 \text{ kg/m}^3},$   
 $W = mg = \rho Vg = 1.473 \times 9.81 \times 10 = \underline{145 \text{ N}}$

ii)  $P = \frac{RT}{v} = \frac{0.287 \times 673}{0.08} = \underline{2410 \text{ kPa}}, \quad \rho = \frac{1}{v} = \frac{1}{0.08} = \underline{12.5 \text{ kg/m}^3},$   
 $W = mg = \rho Vg = 12.5 \times 9.81 \times 10 = \underline{1230 \text{ N}}$

iii)  $40 = mg = \rho Vg = \rho \times 10 \times 9.81. \quad \therefore \rho = \underline{0.4077 \text{ kg/m}^3}, \quad v = \frac{1}{\rho} = \frac{1}{0.4077} = \underline{2.45 \text{ m}^3/\text{kg}},$   
 $T = \frac{Pv}{R} = \frac{600 \times 2.45}{0.287} = 5130 \text{ K, or } \underline{4850^\circ\text{C}}$

iv)  $v = \frac{1}{\rho} = \frac{1}{20} = \underline{0.05 \text{ m}^3/\text{kg}}, \quad P = \frac{RT}{v} = \frac{0.287 \times 233}{0.05} = \underline{1337 \text{ kPa}},$   
 $W = mg = \rho Vg = 20 \times 10 \times 9.81 = \underline{1960 \text{ N}}$

**2.69** Given:  $V = 0.8 \text{ m}^3$

i)  $v = \frac{RT}{P} = \frac{0.287 \times 480}{140} = \underline{0.984 \text{ m}^3/\text{kg}}, \quad \rho = \frac{1}{v} = \frac{1}{0.984} = \underline{1.016 \text{ kg/m}^3},$   
 $W = mg = \rho Vg = 1.016 \times 0.8 \times 9.806 = \underline{7.97 \text{ N}}$

ii)  $P = \frac{RT}{v} = \frac{0.287 \times 590}{0.35} = \underline{484 \text{ kPa}}, \quad \rho = \frac{1}{v} = \frac{1}{0.35} = \underline{2.86 \text{ kg/m}^3},$   
 $W = mg = \rho Vg = 2.86 \times 0.8 \times 9.806 = \underline{22.4 \text{ N}}$

iii)  $W = mg = \rho Vg = \rho \times 0.8 \times 9.806 = 24. \quad \therefore \rho = \underline{3.06 \text{ kg/m}^3}$

$$v = \frac{1}{\rho} = \frac{1}{3.06} = \underline{0.327 \text{ m}^3/\text{kg}}, \quad T = \frac{Pv}{R} = \frac{700 \times 0.327}{0.287} = \underline{797 \text{ K}} = \underline{524^\circ\text{C}}$$

iv)  $P = \rho RT = 26 \times 0.287 \times 223 = \underline{1664 \text{ kPa}}, \quad v = \frac{1}{\rho} = \frac{1}{26} = \underline{0.038 \text{ kg/m}^3},$   
 $W = mg = \rho Vg = 26 \times 0.8 \times 9.806 = \underline{204 \text{ N}}$

**2.70** Inside the house  $T = 22^\circ\text{C}$  or  $295\text{ K}$ . If we assume that the pressure is  $100\text{ kPa}$ ,

$$\rho_{\text{inside}} = \frac{P}{RT} = \frac{100}{0.287 \times 295} = 1.181\text{ kg/m}^3$$

Outside the house  $T = -28^\circ\text{C}$  or  $245\text{ K}$ . We again assume that the pressure is atmospheric.

$$\rho_{\text{outside}} = \frac{P}{RT} = \frac{100}{0.287 \times 245} = 1.422\text{ kg/m}^3$$

$$\therefore \Delta\rho = 1.422 - 1.181 = \underline{0.241\text{ kg/m}^3}$$

The change in density will cause the chimney effect: lighter particles rise and heavier particles fall. Hence, there exists a migration of air particles from the high density region to the low density region, i.e., from the inside to the outside near the top of the house. The heavier particles then enter near the bottom of the walls to take the place of the vacating particles.

**2.71**  $\frac{P_2}{P_1} = \frac{RT_2}{RT_1} \cdot \frac{v_1}{v_2} = \frac{T_2}{T_1} = \frac{343}{250} = 1.372$  with  $v_2 = v_1$ . Then, the pressure in Arizona is

$$P_2 = P_1 \times 1.372 = (250 + 100) \times 1.372 = 480\text{ kPa} \text{ or } \underline{380\text{ kPa gage}}$$

Don't multiply  $250\text{ kPa}$  by  $1.38$ . You must use absolute pressures in the ideal gas equation.

**2.72** Since the drag force is directly proportional to the density of the air, the higher the density the greater the drag force, which will cause the ball to not travel as far. The question is: Is humid air more dense or less dense than dry air? Consider the ideal gas law  $\rho = P/RT$ :

$$\rho_{\text{air}} = \frac{P}{R_{\text{dry air}} T} = \frac{P}{0.287T} \quad \text{and} \quad \rho_{\text{humid}} = \frac{P}{R_{\text{steam}} T} = \frac{P}{0.462T}. \quad \therefore \rho_{\text{dry air}} = 1.61\rho_{\text{humid}}$$

The density of the dry air is greater than the density of humid air so the drag is greater on a dry day, contrary to what all those crazy golfers think! It is more uncomfortable on a humid day but we're talking about distance! If it weren't for the ideal gas law, the ball would travel further on that dry day. Was it the liberals or the conservatives who made up that law?

**2.73** Find the gas constant  $R$  for nitrogen in Table B-2:

i) Using the ideal gas law,

$$v = \frac{RT}{P} = \frac{0.297 \times 130}{4000} = \underline{0.00965\text{ m}^3/\text{kg}}$$

ii) From Fig. 2.22 for  $P = 4\text{ MPa}$  and  $T = 130\text{ K}$ , we get  $Z = 0.4$ . Then

$$v = \frac{ZRT}{P} = \frac{0.4 \times 0.297 \times 130}{4000} = \underline{0.00386\text{ m}^3/\text{kg}}$$

The ideal gas law does not give acceptable results at high pressures and low temperatures. That combination is uncommon in our introductory course so it is not encountered very often.

**2.74** Given:  $m = 10 \text{ kg}$ ,  $V = 1 \text{ m}^3$ , and  $T = -40^\circ\text{C}$  or  $233 \text{ K}$ .  $\therefore v = \frac{1}{10} = 0.1 \text{ m}^3/\text{kg}$ .

a) i) Use Table B-2 for the gas constant of air. The pressure, using the ideal gas law, is

$$P = \frac{RT}{v} = \frac{0.287 \times 233}{0.1} = \underline{669 \text{ kPa}}$$

ii) The critical temperature and pressure for air are found in Table B-3:  $133 \text{ K}$ ,  $3.77 \text{ MPa}$ . The coefficients for van der Waals equation (2.17) are found in Table B-10:

$$P = \frac{RT}{v-b} - \frac{a}{v^2} = \frac{0.287 \times 233}{0.1 - 0.00127} - \frac{0.163}{0.1^2} = \underline{661 \text{ kPa}}$$

b) Table 2.3 in Section 2.5 gives the coefficients of the Beattie-Bridgeman equation (2.19) for air.

$$A_0 = 131.84, B_0 = 0.04611, a = 0.01931, b = 0.0011, c = 4.34 \times 10^4$$

The molar specific volume for air is  $\bar{v} = vM = 0.1 \frac{\text{m}^3}{\text{kg}} \times 28.97 \frac{\text{kg}}{\text{kmol}} = 2.90 \text{ m}^3/\text{kmol}$

$$\begin{aligned} P &= \frac{R_u T}{\bar{v}^2} \left( 1 - \frac{c}{\bar{v} T^3} \right) \left[ \bar{v} + B_0 \left( 1 - \frac{b}{\bar{v}} \right) \right] - \frac{A_0}{\bar{v}^2} \left( 1 - \frac{a}{\bar{v}} \right) \\ &= \frac{8.314 \times 233}{2.90^2} \left( 1 - \frac{4.34 \times 10^4}{2.9 \times 233^3} \right) \left[ 2.9 + 0.0461 \left( 1 - \frac{.0011}{2.90} \right) \right] - \frac{132}{2.9^2} \left( 1 - \frac{.0193}{2.90} \right) = \underline{662 \text{ kPa}} \end{aligned}$$

c) Use the estimate of the pressure from Part (i) to find  $P_R$ :

$$P_R = \frac{P}{P_{cr}} = \frac{669}{3770} = 0.177, \quad T_R = \frac{T}{T_{cr}} = \frac{233}{133} = 1.75$$

From Appendix Fig. H-1 for  $T_R = 1.75$  and  $P_R = 0.177$ , the compressibility factor is about 0.99. This provides a pressure of  $P = 0.99 \times 669 = \underline{662 \text{ kPa}}$ .

d) The IRC calculator for dry air at  $-40^\circ\text{C}$  and a density of  $10 \text{ kg/m}^3$  provides  $P = \underline{664 \text{ kPa}}$ .

**2.75** The working fluid is nitrogen at  $-60^\circ\text{C}$  or  $213 \text{ K}$  with a specific volume of  $0.036 \text{ m}^3/\text{kg}$ .

i) The ideal gas law is used to find  $P = \frac{RT}{v} = \frac{0.297 \times 213}{0.036} = 1757 \text{ kPa}$

ii) Find the van der Waals coefficients in Table B-10. Equation (2.17) provides

$$P = \frac{RT}{v-b} - \frac{a}{v^2} = \frac{0.297 \times 213}{0.036 - 0.00138} - \frac{0.1747}{0.036^2} = 1692.5 \text{ kPa}$$

iii) Use the estimate of the pressure from Part (i) to find  $P_R$ :

$$P_R = \frac{P}{P_{cr}} = \frac{1757}{3390} = 0.52, \quad T_R = \frac{T}{T_{cr}} = \frac{213}{126.2} = 1.68$$

From Fig. H-1,  $Z \cong 0.86$  so  $P = 0.86 \times 1757 = \underline{1511 \text{ kPa}}$ .

**2.76** For air at 60 kPa and  $-80^{\circ}\text{C}$  or 193K.

i) The ideal gas law is used to give

$$v = \frac{RT}{P} = \frac{0.287 \times 193}{60} = \underline{0.923 \text{ m}^3/\text{kg}}$$

ii) The critical constants for air from Table B-3 are  $T_{cr} = 133 \text{ K}$  and  $P_{cr} = 3.77 \text{ MPa}$ . Use Table B-10 for the van der Waals coefficients and Eq. 2.17 for  $v$ :

$$P = \frac{RT}{v-b} - \frac{a}{v^2} \quad \text{or} \quad 60 = \frac{0.287 \times 193}{v - 0.00127} - \frac{0.163}{v^2}$$

This equation is solved for  $v$  **by trial and error**. Use the value from Part (i) as a start:

$$\text{For } v = 0.923, 60 \stackrel{?}{=} 59.9. \quad \text{For } v = 0.92, 60 \stackrel{?}{=} 60.1. \quad \therefore v = \underline{0.921 \text{ m}^3/\text{kg}}.$$

$$\text{iii) } P_R = \frac{P}{P_{cr}} = \frac{60}{3770} = 0.016, \quad T_R = \frac{T}{T_{cr}} = \frac{193}{133} = 1.45$$

Using Table H-2 we get  $Z \approx 0.995$ .  $v = \underline{0.92 \text{ m}^3/\text{kg}}$

iv) The IRC Calculator for dry air at  $-80^{\circ}\text{C}$  and a pressure of 60 kPa gives  $v = \underline{0.923 \text{ m}^3/\text{kg}}$ .

**2.77** The specific heats are listed in Table B-2.

a) For air  $C_p = 1.00 \text{ kJ/kg}^{\circ}\text{C}$ ,  $\Delta h = 1.00 \times (450^{\circ}\text{C} - 20^{\circ}\text{C}) = \underline{430 \text{ kJ/kg}}$

b) For nitrogen  $C_p = 1.042 \text{ kJ/kg}^{\circ}\text{C}$ ,  $\Delta h = 1.042 \times (450 - 20) = \underline{448 \text{ kJ/kg}}$

c) For hydrogen  $C_p = 14.209 \text{ kJ/kg}^{\circ}\text{C}$ ,  $\Delta h = 14.209 \times (450 - 20) = \underline{6110 \text{ kJ/kg}}$

d) For propane  $C_p = 1.679 \text{ kJ/kg}^{\circ}\text{C}$ ,  $\Delta h = 1.679 \times (450 - 20) = \underline{722 \text{ kJ/kg}}$

e) For steam  $C_p = 1.872 \text{ kJ/kg}^{\circ}\text{C}$ ,  $\Delta h = 1.872 \times (450 - 20) = \underline{805 \text{ kJ/kg}}$

**2.78 State 1:**  $T_1 = 30^{\circ}\text{C}$  and  $x_1 = 1$  (Steam is very near an ideal gas at this state: check  $v_g = RT/P$ .)

**State 2:**  $T_2 = 150^{\circ}\text{C}$  and  $P_2 = 200 \text{ kPa}$

i) For steam, we use Table B-2 to get  $C_p = 1.872 \text{ kJ/kg}^{\circ}\text{C}$

$$\therefore \Delta h = C_p \Delta T = 1.872(150 - 30) = \underline{225 \text{ kJ/kg}}$$

ii) From Table C-1,  $h_1 = h_g = 2556.2 \text{ kJ/kg}$ . From Table C-3,  $h_2 = 2768.8 \text{ kJ/kg}$

$$\therefore \Delta h = 2768.8 - 2556.2 = \underline{213 \text{ kJ/kg}}$$

iii) Using the IRC calculator, we obtain  $h_1 = 2560 \text{ kJ/kg}$  and  $h_2 = 2770 \text{ kJ/kg}$

$$\therefore \Delta h = 2770 - 2560 = \underline{210 \text{ kJ/kg}}$$

**2.79 a)** i) Table B-2 gives the constant specific heats for nitrogen:

$$\Delta u = 0.745 \text{ kJ/kg}^\circ\text{C}(500^\circ - 20^\circ) = \underline{357.6 \text{ kJ/kg}}$$

$$\Delta h = 1.042 \text{ kJ/kg}^\circ\text{C}(500^\circ - 20^\circ) = \underline{479 \text{ kJ/kg}}$$

ii) Use Table F-2 for the molar internal energies and enthalpies:

$$\Delta u = \frac{16599 \text{ kJ/kmol} - 6190 \text{ kJ/kmol}}{28 \text{ kg/kmol}} = \underline{371 \text{ kJ/kg}}$$

$$\Delta h = \frac{23085 \text{ kJ/kmol} - 8669 \text{ kJ/kmol}}{28 \text{ kg/kmol}} = \underline{514 \text{ kJ/kg}}$$

b) The average temperature is  $T_{\text{av}} = (500^\circ + 20^\circ)/2 = 260^\circ\text{C}$  or  $533\text{K}$

$$\bar{C}_p = 28.9 - 0.001571 \times 533 + 0.8081 \times 10^{-5} \times 533^2 - 2.873 \times 10^{-9} \times 533^3$$

$$= 29.9 \text{ kJ/kmol} \cdot \text{K}$$

$$C_p = \frac{29.9 \text{ kJ/kmol} \cdot \text{K}}{28 \text{ kg/kmol}} = 1.068 \text{ kJ/kg} \cdot \text{K}$$

$$C_v = C_p - R = 1.068 - 0.2968 = 0.771 \text{ kJ/kg} \cdot \text{K}$$

$$\Delta u = 0.771 \times (500 - 20) = \underline{370 \text{ kJ/kg}}, \quad \Delta h = 1.068 \times (500 - 20) = \underline{513 \text{ kJ/kg}}$$

c)  $C_p = 1.0317 - 5.6 \times 10^{-5} \times 533 + 2.88 \times 10^{-7} \times 533^2 - 1.02 \times 10^{-10} \times 533^3 = 1.068 \text{ kJ/kg} \cdot \text{K}$

$$C_v = C_p - R = 1.068 - 0.2968 = 0.771 \text{ kJ/kg} \cdot \text{K}$$

$$\therefore \Delta u = 0.771 \times (500 - 20) = \underline{370 \text{ kJ/kg}}, \quad \Delta h = 1.068 \times (500 - 20) = \underline{513 \text{ kJ/kg}}$$

**2.80**  $m = 10 \text{ kg}$  of air and  $\Delta T = 540^\circ\text{C}$

a) i) From Table B-2 for air  $C_v = 0.717 \text{ kJ/kg} \cdot \text{K}$  and  $C_p = 1.003 \text{ kJ/kg} \cdot \text{K}$ :

$$\Delta U = mC_v \Delta T = 10 \times 0.717 \times 540 = \underline{3872 \text{ kJ}}$$

$$\Delta H = mC_p \Delta T = 10 \times 1.003 \times 540 = \underline{5416 \text{ kJ}}$$

ii) From Appendix F-1: for air at  $-4^\circ\text{C}$  we get  $u_1 = 193.3 \text{ kJ/kg}$  and  $h_1 = 271.1 \text{ kJ/kg}$  by interpolation. For air at  $536^\circ\text{C}$ ,  $u_2 = 599.7 \text{ kJ/kg}$  and  $h_2 = 832.6 \text{ kJ/kg}$ .

$$\Delta U = 10 \times (599.7 - 193.3) = \underline{4064 \text{ kJ}}$$

$$\Delta H = 10 \times (832.6 - 271.1) = \underline{5615 \text{ kJ}}$$

b) Table B-6 is in SI units only.  $T_1 = 271 \text{ K}$ ,  $T_2 = 809 \text{ K}$ ,  $T_{\text{av}} = 540 \text{ K}$  For air:

Table B-6 provides  $C_v = 0.751 \text{ kJ/kg} \cdot \text{K}$  and  $C_p = 1.04 \text{ kJ/kg} \cdot \text{K}$  (it is not necessary to be exact in the relatively easy interpolation), so

$$\Delta U = mC_v \Delta T = 10 \times 0.751 \times (809 - 271) = 4040 \text{ kJ}$$

$$\Delta H = mC_p \Delta T = 10 \times 1.04 \times (809 - 271) = 5595 \text{ kJ}$$

c) Again, we solve the problem in SI units:

$$C_p = 0.9703 + 6.8 \times 10^{-5} T + 1.66 \times 10^{-7} T^2 + 6.8 \times 10^{-11} T^3$$

At the average temperature of 540 K,  $C_p = 1.066$  kJ/kgK. Then

$$\begin{aligned} C_v &= C_p - R = 1.066 - 0.287 = 0.779 \text{ kJ/kg} \cdot \text{K} \\ \Delta U &= m C_v \Delta T = 10 \times 0.779 \times (809 - 271) = 4191 \text{ kJ} \\ \Delta H &= m C_p \Delta T = 10 \times 1.066 \times (809 - 271) = 5735 \text{ kJ} \end{aligned}$$

d) The IRC Calculator provides the internal energies and enthalpies for dry air at both temperatures.

$$\begin{aligned} \Delta U &= 10 \times (600 - 192) = \underline{4080 \text{ kJ}} \\ \Delta H &= 10 \times (833 - 269) = \underline{5640 \text{ kJ}} \end{aligned}$$

**2.81** For steam at 1600 kPa and 400°C, we use Table C-3 for the following enthalpies:

$T$ (°C)	$h$ (kJ/kg)
300	3034.8
350	3145.4
400	3254.2
500	3472

i) Using backward differencing at 350°C and 400°C, there results

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3254.2 - 3145.4}{50^\circ\text{C}} = \underline{2.18 \text{ kJ/kg} \cdot ^\circ\text{C}}$$

ii) Use forward differencing at 350°C and 400°C:  $C_p = \frac{\Delta h}{\Delta T} = \frac{3472 - 3254.2}{100} = \underline{2.18 \text{ kJ/kg} \cdot ^\circ\text{C}}$

iii) Use central differencing at 300°C and 500°C (the intervals must be the same):

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3472 - 3145.4}{150} = \underline{2.18 \text{ kJ/kg} \cdot ^\circ\text{C}}$$

iv) For steam at 300 K from Table B-2,  $C_p = \underline{1.872 \text{ kJ/kg} \cdot ^\circ\text{C}}$

The curve  $C_p(T)$  does not have sufficient curvature for a difference to appear in the three difference methods; however, central differencing should give the most accurate value of  $C_p$  at 400°C.

**2.82** Use the enthalpy data for steam from Table C-3.

a)  $P = 0.2$  MPa and  $T = 400^\circ\text{C}$ . We will use central differencing between 300° and 500° to estimate the specific heat at 400°:

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3487.1 - 3071.8}{200} = \underline{2.08 \text{ kJ/kg} \cdot ^\circ\text{C}}$$

- b)  $P = 1.8 \text{ MPa}$  and  $T = 400^\circ\text{C}$ . We will use central differencing between  $300^\circ$  and  $500^\circ$  to estimate the specific heat at  $400^\circ$ :

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3469.8 - 3029.2}{200} = \underline{2.20 \text{ kJ/kg} \cdot ^\circ\text{C}}$$

- c)  $P = 7 \text{ MPa}$  and  $T = 400^\circ\text{C}$ . We will use central differencing between  $350^\circ$  and  $450^\circ$  to estimate the specific heat at  $400^\circ$ :

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3287.1 - 3016}{100} = \underline{2.71 \text{ kJ/kg} \cdot ^\circ\text{C}}$$

**2.83** Using enthalpy data for steam from Table C-3.

- a)  $P = 300 \text{ kPa}$  and  $T = 300^\circ\text{C}$ . We will use central differencing between  $250^\circ\text{C}$  and  $350^\circ\text{C}$  to get the specific heat at  $300^\circ\text{C}$ .

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3174.2 - 2971}{100} = \underline{2.032 \text{ kJ/kg} \cdot \text{K}}$$

- b)  $P = 1 \text{ MPa}$  and  $T = 300^\circ\text{C}$ . We will use central differencing between  $250^\circ\text{C}$  and  $350^\circ\text{C}$  to get the specific heat at  $300^\circ\text{C}$ .

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3157.7 - 2942.6}{100} = \underline{2.151 \text{ kJ/kg} \cdot \text{K}}$$

- c)  $P = 4 \text{ MPa}$  and  $T = 300^\circ\text{C}$ . We will use central differencing between  $250^\circ\text{C}$  and  $350^\circ\text{C}$  to get the specific heat at  $300^\circ\text{C}$ .

$$C_p = \frac{\Delta h}{\Delta T} = \frac{3092.5 - 2801}{100} = \underline{2.91 \text{ kJ/kg} \cdot \text{K}}$$

**2.84** 40 kg of water is heated at 100 kPa from  $16^\circ\text{C}$  to  $92^\circ\text{C}$ . The water will exist as a subcooled liquid. The compressed liquid properties will be approximated by the saturated liquid properties. Use Table C.1 to get the internal energies and enthalpies:

At  $16^\circ\text{C}$ ,  $u_1 = u_f = 67.18 \text{ kJ/kg}$  and  $h_1 = h_f = 67.18 \text{ kJ/kg}$ .

At  $92^\circ\text{C}$ ,  $u_2 = u_f = 385.2 \text{ kJ/kg}$  and  $h_2 = h_f = 385.3 \text{ kJ/kg}$

$$\Delta U = 40 \times (385.2 - 67.18) = \underline{12\,720 \text{ kJ}}$$

$$\Delta H = 40 \times (385.3 - 67.18) = \underline{12\,720 \text{ kJ}}$$

The actual difference is  $\Delta h - \Delta u = \Delta(Pv) = P\Delta v = 100 \times (0.001038 - 0.001001) = 0.0037 \text{ kJ/kg}$  or  $3.7 \text{ J/kg}$

**2.85** From Table B-4 we get for mercury at  $10^\circ\text{C}$  and 1 atm a value of  $C_p = 0.138 \text{ kJ/kg} \cdot ^\circ\text{C}$ .

$$\Delta H = mC_p\Delta T = 5 \times 0.138 \times \Delta T = 200 \text{ kJ}$$

$$\therefore \Delta T = 290^\circ\text{C} \quad T_{\text{final}} = 25^\circ\text{C} + 290^\circ\text{C} = \underline{315^\circ\text{C}} \text{ . (Mercury boils at } 357^\circ\text{C}.)$$



**2.86** In this problem, 10 kg of ice at  $-20^{\circ}\text{C}$  is heated to become liquid water at  $50^{\circ}\text{C}$ . The phase change occurs at  $0^{\circ}\text{C}$  since the pressure is presumably atmospheric.

a) If  $C_p = 2.1 \text{ kJ/kg}\cdot^{\circ}\text{C}$ , the enthalpy change of the ice is

$$\Delta H_{\text{ice}} = mC_p\Delta T = 10 \times 2.1 \times [0 - (-20)] = 420 \text{ kJ}$$

As stated on Section 2.2.4, the heat of fusion for ice is  $330 \text{ kJ/kg}$ , so that

$$\Delta H_{\text{melt}} = 10 \text{ kg} \times 330 \text{ kJ/kg} = 3300 \text{ kJ}$$

To heat the liquid water from  $0^{\circ}\text{C}$  to  $50^{\circ}\text{C}$ , use  $C_p$  from Table B-4:

$$\Delta H_{\text{liquid}} = mC_p\Delta T = 10 \times 4.177 \times 50 = 2090 \text{ kJ}$$

$$\therefore \Delta H_{\text{total}} = 420 \text{ kJ} + 3300 \text{ kJ} + 2090 \text{ kJ} = \underline{5810 \text{ kJ}}$$

b) Use the equation  $C_{p, \text{ice}} = 2.1 + 0.0069T$ :

$$\begin{aligned} \Delta H_{\text{ice}} &= m \int_1^2 C_p dT \\ &= 10 \int_{-20}^0 (2.1 + 0.0069T) dT = 10 \left[ 2.1(0 + 20) + 0.0069 \frac{0^2 - 20^2}{2} \right] = 434 \text{ kJ} \end{aligned}$$

As stated on Section 2.2.4, the heat of fusion for ice is  $330 \text{ kJ/kg}$ , so that

$$\Delta H_{\text{melt}} = 10 \text{ kg} \times 330 \text{ kJ/kg} = 3300 \text{ kJ}$$

To heat the liquid water from  $0^{\circ}\text{C}$  to  $50^{\circ}\text{C}$ , use  $C_p$  from Table B-4:

$$\Delta H_{\text{liquid}} = mC_p\Delta T = 10 \times 4.177 \times 50 = 2090 \text{ kJ}$$

$$\therefore \Delta H_{\text{total}} = 434 \text{ kJ} + 3300 \text{ kJ} + 2090 \text{ kJ} = \underline{5820 \text{ kJ}}$$