Chapter 2 Solutions
Engineering and Chemical Thermodynamics

Wyatt Tenhaeff
Milo Koretsky

Department of Chemical Engineering
Oregon State University

koretsm@engr.orst.edu

2.1

There are many possible solutions to this problem. Assumptions must be made to solve the problem. One solution is as follows. First, assume that half of a kilogram is absorbed by the towel when you dry yourself. In other words, let

$$m_{H_2O} = 0.5\,[\text{kg}]$$

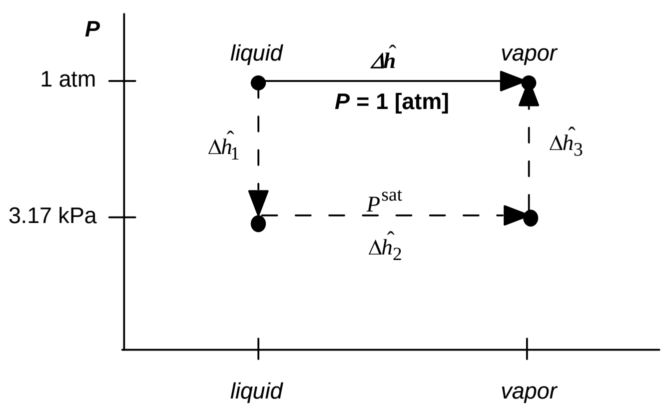
Assume that the pressure is constant at 1.01 bar during the drying process. Performing an energy balance and neglecting potential and kinetic energy effects reveals

$$\hat{q} = \Delta\hat{h}$$

Refer to the development of Equation 2.57 in the text to see how this result is achieved. To find the minimum energy required for drying the towel, assume that the temperature of the towel remains constant at $T = 25\,^{\circ}\text{C} = 298.15\,\text{K}$. In the drying process, the absorbed water is vaporized into steam. Therefore, the expression for heat is

$$\hat{q} = \hat{h}^{v}_{H_2O} - \hat{h}^{l}_{H_2O}$$

where is $\hat{h}^{v}_{H_2O}$ is the specific enthalpy of water vapor at $P = 1.01\,\text{bar}$ and $T = 298.15\,\text{K}$ and $\hat{h}^{l}_{H_2O}$ is the specific enthalpy of liquid water at $P = 1.01\,\text{bar}$ and $T = 298.15\,\text{K}$. A hypothetical path must be used to calculate the change in enthalpy. Refer to the diagram below



By adding up each step of the hypothetical path, the expression for heat is

$$\begin{aligned}\hat{q} &= \Delta h_1 + \Delta h_2 + \Delta h_3 \\ &= \left[\hat{h}^{l,sat}_{H_2O}(25\,^{\circ}\text{C}) - \hat{h}^{l}_{H_2O}(25\,^{\circ}\text{C}, 1.01\,\text{bar})\right] + \left[\hat{h}^{v,sat}_{H_2O}(25\,^{\circ}\text{C}) - \hat{h}^{l,sat}_{H_2O}(25\,^{\circ}\text{C})\right] \\ &\quad + \left[\hat{h}^{v}_{H_2O}(25\,^{\circ}\text{C}, 1.01\,\text{bar}) - \hat{h}^{v,sat}_{H_2O}(25\,^{\circ}\text{C})\right]\end{aligned}$$

However, the calculation of heat can be simplified by treating the water vapor as an ideal gas, which is a reasonable assumption at low pressure. The enthalpies of ideal gases depend on temperature only. Therefore, the enthalpy of the vapor change due to the pressure change is zero. Furthermore, enthalpy is weakly dependent on pressure in liquids. The leg of the hypothetical path containing the pressure change of the liquid can be neglected. This leaves

$$\hat{q} = \hat{h}^{v}_{H_2O}\left(25\,^{o}\text{C}, 3.17\text{ kPa}\right) - \hat{h}^{l}_{H_2O}\left(25\,^{o}\text{C}, 3.17\text{ kPa}\right)$$

From the steam tables:

$$\hat{h}^{v,sat}_{H_2O} = 2547.2\left[\frac{\text{kJ}}{\text{kg}}\right] \qquad \text{(sat. } H_2O \text{ vapor at 25 ºC)}$$

$$\hat{h}^{l,sat}_{H_2O} = 104.87\left[\frac{\text{kJ}}{\text{kg}}\right] \qquad \text{(sat. } H_2O \text{ liquid at 25 ºC)}$$

which upon substitution gives

$$\hat{q} = 2442.3\left[\frac{\text{kJ}}{\text{kg}}\right]$$

Therefore,

$$Q = (0.5\,[\text{kg}])\left(2442.3\left[\frac{\text{kJ}}{\text{kg}}\right]\right) = 1221.2\,[\text{kJ}]$$

To find the efficiency of the drying process, assume the dryer draws 30 A at 208 V and takes 20 minutes (1200 s) to dry the towel. From the definition of electrical work,

$$W = IVt = (30\,[\text{A}])(208\,[\text{V}])(1200\,[\text{s}]) = 7488\,[\text{kJ}]$$

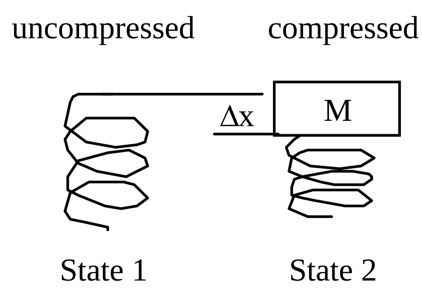
Therefore, the efficiency is

$$\eta = \left(\frac{Q}{W}\times 100\right)\% = \left(\frac{1221.2\,[\text{kJ}]}{7488\,[\text{kJ}]}\times 100\right)\% = 16.3\%$$

There are a number of ways to improve the drying process. A few are listed below.

- Dry the towel outside in the sun.
- Use a smaller volume dryer so that less air needs to be heated.
- Dry more than one towel at a time since one towel can’t absorb all of the available heat. With more towels, more of the heat will be utilized.

2.3
In answering this question, we must distinguish between potential energy and internal energy. The potential energy of a system is the energy the macroscopic system, as a whole, contains relative to position. The internal energy represents the energy of the individual atoms and molecules in the system, which can have contributions from both molecular kinetic energy and molecular potential energy. Consider the compression of a spring from an initial uncompressed state as shown below.



Since it requires energy to compress the spring, we know that some kind of energy must be stored within the spring. Since this change in energy can be attributed to a change of the macroscopic position of the system and is not related to changes on the molecular scale, we determine the form of energy to be potential energy. In this case, the spring's tendency to restore its original shape is the driving force that is analogous to the gravity for gravitational potential energy.

This argument can be enhanced by the form of the expression that the increased energy takes. If we consider the spring as the system, the energy it acquires in a reversible, compression from its initial uncompressed state may be obtained from an energy balance. Assuming the process is adiabatic, we obtain:

$$\Delta E = Q + W = W$$

We have left the energy in terms of the total energy, *E*. The work can be obtained by integrating the force over the distance of the compression:

$$W = -\int F \cdot dx = \int kx dx = \frac{1}{2}kx^2$$

Hence:

$$\Delta E = \frac{1}{2}kx^2$$

We see that the increase in energy depends on macroscopic position through the term *x*.

It should be noted that there is a school of thought that assigns this increased energy to internal energy. This approach is all right as long as it is consistently done throughout the energy balances on systems containing springs.

2.4
For the first situation, let the rubber band represent the system. In the second situation, the gas is the system. If heat transfer, potential and kinetic energy effects are assumed negligible, the energy balance becomes

$$\Delta U = W$$

Since work must be done on the rubber band to stretch it, the value of the work is positive. From the energy balance, the change in internal energy is positive, which means that the temperature of the system rises.

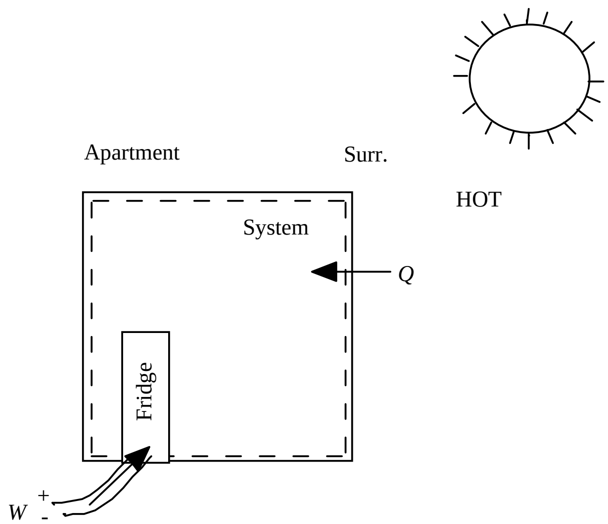
When a gas expands in a piston-cylinder assembly, the system must do work to expand against the piston and atmosphere. Therefore, the value of work is negative, so the change in internal energy is negative. Hence, the temperature decreases.

In analogy to the spring in Problem 2.3, it can be argued that some of the work imparted into the rubber band goes to increase its potential energy; however, a part of it goes into stretching the polymer molecules which make up the rubber band, and the qualitative argument given above still is valid.

2.5

To explain this phenomenon, you must realize that the water droplet is heated from the bottom. At sufficiently high temperatures, a portion of the water droplet is instantly vaporized. The water vapor forms an insulation layer between the skillet and the water droplet. At low temperatures, the insulating layer of water vapor does not form. The transfer of heat is slower through a gas than a liquid, so it takes longer for the water to evaporate at higher temperatures.

2.6



If the entire apartment is treated as the system, then only the energy flowing across the apartment boundaries (apartment walls) is of concern. In other words, the energy flowing into or out of the refrigerator is not explicitly accounted for in the energy balance because it is within the system. By neglecting kinetic and potential energy effects, the energy balance becomes

$$\Delta U = Q + W$$

The Q term represents the heat from outside passing through the apartment's walls. The W term represents the electrical energy that must be supplied to operate the refrigerator.

To determine whether opening the refrigerator door is a good idea, the energy balance with the door open should be compared to the energy balance with the door closed. In both situations, Q is approximately the same. However, the values of W will be different. With the door open, more electrical energy must be supplied to the refrigerator to compensate for heat loss to the apartment interior. Therefore,

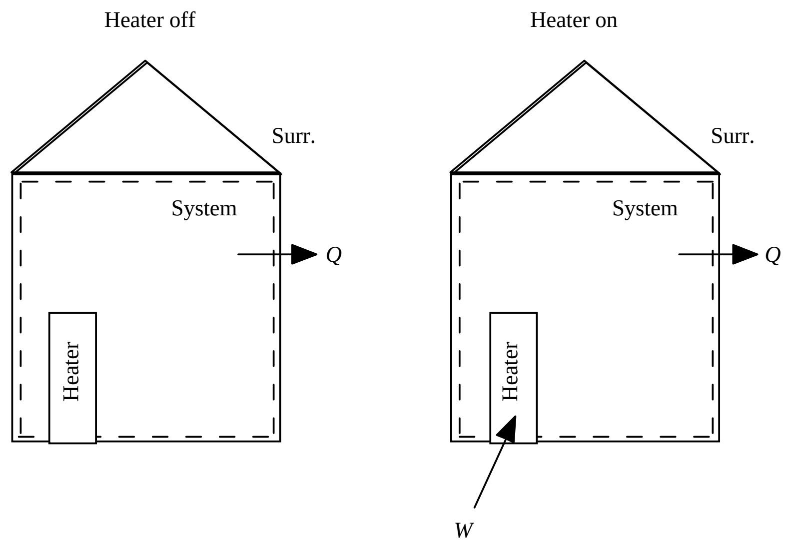
$$W_{ajar} > W_{shut}$$

where the subscript "ajar" refers the situation where the door is open and the subscript "shut" refers to the situation where the door is closed. Since,

$$Q_{ajar} = Q_{shut}$$
$$\Delta U_{ajar} = Q_{ajar} + W_{ajar} > \Delta U_{shut} = Q_{shut} + W_{shut}$$
$$\therefore \Delta T_{ajar} > \Delta T_{shut}$$

The refrigerator door should remain closed.

2.7
The two cases are depicted below.



Let's consider the property changes in your house between the following states. State 1, when you leave in the morning, and state, the state of your home after you have returned home and heated it to the same temperature as when you left. Since *P* and *T* are identical for states 1 and 2, the state of the system is the same and *ΔU* must be zero, so

$$\Delta U = Q + W = 0$$

or

$$-Q = W$$

where -*Q* is the total heat that escaped between state 1 and state 2 and *W* is the total work that must be delivered to the heater. The case where more heat escapes will require more work and result in higher energy bills. When the heater is on during the day, the temperature in the system is greater than when it is left off. Since heat transfer is driven by difference in temperature, the heat transfer rate is greater, and *W* will be greater. Hence, it is cheaper to leave the heater off when you are gone.

2.8

The amount of work done at constant pressure can be calculated by applying Equation 2.57

$$\Delta H = Q$$

Hence,

$$\Delta H = Q = m\Delta \hat{h}$$

where the specific internal energy is used in anticipation of obtaining data from the steam tables. The mass can be found from the known volume, as follows:

$$m = \frac{V}{\hat{v}} = \frac{(1[\text{L}])\left(0.001\left[\frac{\text{m}^3}{\text{L}}\right]\right)}{\left(0.0010\left[\frac{\text{m}^3}{\text{kg}}\right]\right)} = 1.0\,[\text{kg}]$$

As in Example 2.2, we use values from the saturated steam tables at the same temperature for subcooled water at 1 atm. The specific enthalpy is found from values in Appendix B.1:

$$\Delta\hat{u} = \hat{u}_{l,2}\left(\text{at}\,100\left[^{\text{o}}\text{C}\right]\right) - \hat{u}_{l,1}\left(\text{at}\,25\left[^{\text{o}}\text{C}\right]\right) = 419.02\left[\frac{\text{kJ}}{\text{kg}}\right] - 104.87\left[\frac{\text{kJ}}{\text{kg}}\right] = 314.15\left[\frac{\text{kJ}}{\text{kg}}\right]$$

Solve for heat:

$$Q = m\Delta\hat{u} = (1.0\,[\text{kg}])\left(314.05\left[\frac{\text{kJ}}{\text{kg}}\right]\right) = 314.15\,[\text{kJ}]$$

and heat rate:

$$\dot{Q} = \frac{Q}{t} = \frac{314.15\,[\text{kJ}]}{(10\,[\text{min.}])\left(\frac{60\,[\text{s}]}{\text{min}}\right)} = 0.52\,[\text{kW}]$$

This value is the equivalent of five strong light bulbs.

2.9

(a)
From Steam Tables:

$$\hat{u}_1 = 2967.8\left[\frac{\text{kJ}}{\text{kg}}\right] \qquad \text{(100 kPa, 400 ºC)}$$
$$\hat{u}_2 = 2659.8\left[\frac{\text{kJ}}{\text{kg}}\right] \qquad \text{(50 kPa, 200 ºC)}$$

$$\Delta\hat{u} = \hat{u}_2 - \hat{u}_1 = -308.0\left[\frac{\text{kJ}}{\text{kg}}\right]$$

(b)
From Equations 2.53 and 2.63

$$\Delta u = u_2 - u_1 = \int_{T_1}^{T_2} c_v dT = \int_{T_1}^{T_2} \left(c_P - R\right) dT$$

From Appendix A.2

$$c_P = R(A + BT + CT^2 + DT^{-2} + ET^3)$$
$$\Delta u = R\int_{T_1}^{T_2}\left[A + BT + CT^2 + DT^{-2} + ET^3 - 1\right]dT$$

Integrating

$$\Delta u = R\left[(A-1)(T_2 - T_1) + \frac{B}{2}(T_2{}^2 - T_1{}^2) + \frac{C}{3}(T_2{}^3 - T_1{}^3) - D(\frac{1}{T_2} - \frac{1}{T_1}) + \frac{E}{4}(T_2{}^4 - T_1{}^4)\right]$$

The following values were found in Table A.2.1

$$A = 3.470$$
$$B = 1.45\times10^{-3}$$
$$C = 0$$
$$D = 1.21\times10^{4}$$
$$E = 0$$

Substituting these values and using

$$R = 8.314\left[\frac{\text{J}}{\text{mol}\cdot\text{K}}\right]$$
$$T_1 = (400 + 273.15\ \text{K}) = 673.15\ \text{K}$$
$$T_2 = (200 + 273.15\ \text{K}) = 473.15\ \text{K}$$

provides

$$\Delta u = -5551\left[\frac{\text{J}}{\text{mol}}\right]$$
$$\Delta\hat{u} = \left(-5551\left[\frac{\text{J}}{\text{mol}}\right]\right)\left(\frac{1[\text{mol H}_2\text{O}]}{18.0148\,[\text{g H}_2\text{O}]}\right)\left(\frac{1000\ \text{g}}{1\ \text{kg}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{J}}\right) = -308.1\left[\frac{\text{kJ}}{\text{kg}}\right]$$

The values in parts (a) and (b) agree very well. The answer from part (a) will serve as the basis for calculating the percent difference since steam table data should be more accurate.

$$\%Difference = \left|\frac{-308-(-)308.1}{-308.0}\times 100\right|\% = 0.03\%$$

2.10

(a)

Referring to the energy balance for closed systems where kinetic and potential energy are neglected, Equation 2.30 states

$$\Delta U = Q + W$$

(b)

Since internal energy is a function of temperature only for an ideal gas (Equation 2.4) and the process is isothermal

$$\Delta U = 0$$

According to Equation 2.77

$$W = nRT \ln\left(\frac{P_2}{P_1}\right) = n_1 RT_1 \ln\left(\frac{P_2}{P_1}\right)$$

From the ideal gas law:

$$n_1 RT_1 = P_1 V_1$$

$$W = P_1 V_1 \ln\left(\frac{P_2}{P_1}\right)$$

Substitution of the values from the problem statement yields

$$W = \left(8\times10^5 \text{ Pa}\right)\left(2.5\times10^{-3} \text{ m}^3\right)\ln\left(\frac{5 \text{ bar}}{8 \text{ bar}}\right)$$

$$W = -940 \,[\text{J}]$$

The energy balance is

$$0 \text{ J} = Q + W$$

$$\therefore Q = 940 \,[\text{J}]$$

(c)

Since the process is adiabatic

$$Q = 0$$

The energy balance reduces to

$$\Delta U = W$$

The system must do work on the surroundings to expand. Therefore, the work will be negative and

$$\Delta U < 0$$

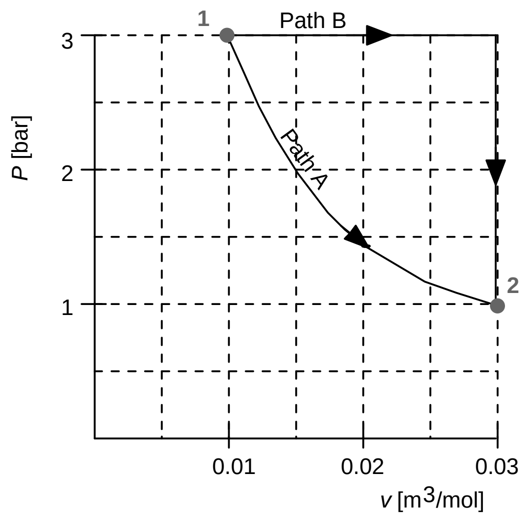
$$\Delta U = n\int_{T_1}^{T_2} c_V \Delta T < 0$$

$$\therefore T_2 < T_1$$

T_2 will be less than 30 ºC

2.11

(a)
(i).



(ii).
Since internal energy is a function of temperature only for an ideal gas (Equation 2.4) and the process is isothermal

$$\boxed{\Delta u = 0}$$

Equation 2.48 states that enthalpy is a function of temperature only for an ideal gas. Therefore,

$$\boxed{\Delta h = 0}$$

Performing an energy balance and neglecting potential and kinetic energy produces

$$\Delta u = q + w = 0$$

For an isothermal, adiabatic process, Equation 2.77 states

$$W = nRT \ln\left(\frac{P_2}{P_1}\right)$$

or

$$w = \frac{W}{n} = RT \ln\left(\frac{P_2}{P_1}\right)$$

Substituting the values from the problem statement gives

$$w = \left(8.314\left[\frac{\text{J}}{\text{mol}\cdot\text{K}}\right]\right)\left((88+273.15)\text{ K}\right)\ln\left(\frac{1\,\text{bar}}{3\,\text{bar}}\right)$$

$$\boxed{w = -3299\left[\frac{\text{J}}{\text{mol}}\right]}$$

Using the energy balance above

$$\boxed{q = -w = 3299\left[\frac{\text{J}}{\text{mol}}\right]}$$

(b)

(i). See path on diagram in part (a)

(ii).

Since the overall process is isothermal and u and h are state functions

$$\boxed{\Delta u = 0}$$
$$\boxed{\Delta h = 0}$$

The definition of work is

$$w = -\int P_E dv$$

During the constant volume part of the process, no work is done. The work must be solved for the constant pressure step. Since it is constant pressure, the above equation simplifies to

$$w = -P_E \int dv = -P_E (v_2 - v_1)$$

The ideal gas law can be used to solve for v_2 and v_1

$$v_2 = \frac{RT_2}{P_2} = \frac{\left(8.314\left[\frac{\text{J}\cdot\text{mol}}{\text{K}}\right]\right)\left((88+273.15)\text{ K}\right)}{1\times10^5\text{ Pa}} = 0.030\left[\frac{\text{m}^3}{\text{mol}}\right]$$

$$v_1 = \frac{RT_1}{P_1} = \frac{\left(8.314\left[\frac{\text{J}\cdot\text{mol}}{\text{K}}\right]\right)\left((88+273.15)\text{ K}\right)}{3\times10^5\text{ Pa}} = 0.010\left[\frac{\text{m}^3}{\text{mol}}\right]$$

Substituting in these values and realizing that $P_E = P_1$ since the process is isobaric produces

$$w = -(3\times10^5\ \text{Pa})\left(0.030\left[\frac{\text{m}^3}{\text{mol}}\right] - 0.010\left[\frac{\text{m}^3}{\text{mol}}\right]\right)$$

$$\boxed{w = -6000\left[\frac{\text{J}}{\text{mol}}\right]}$$

Performing an energy balance and neglecting potential and kinetic energy results in

$$\Delta u = q + w = 0$$

$$\boxed{\therefore q = -w = 6000\left[\frac{\text{J}}{\text{mol}}\right]}$$

2.12

First, perform an energy balance. No work is done, and the kinetic and potential energies can be neglected. The energy balance reduces to

$$\Delta U = Q$$

We can use Equation 2.53 to get

$$Q = n\int_{T_1}^{T_2} c_V dT$$

which can be rewritten as

$$Q = n\int_{T_1}^{T_2} c_P dT$$

since the aluminum is a solid. Using the atomic mass of aluminum we find

$$n = \frac{5\,\text{kg}}{0.02698\left[\frac{\text{kg}}{\text{mol}}\right]} = 185.3\,\text{mol}$$

Upon substitution of known values and heat capacity data from Table A.2.3, we get

$$Q = (185.3\,\text{mol})\left(8.314\left[\frac{\text{J}}{\text{mol}\cdot\text{K}}\right]\right)\int_{294.15\,\text{K}}^{323.15\,\text{K}}\left(2.486 + 1.49\times10^{-3}T\right)dT$$

$$Q = 131.61\,[\text{kJ}]$$

2.13
First, start with the energy balance. Potential and kinetic energy effects can be neglected. Therefore, the energy balance becomes

$$\Delta U = Q + W$$

The value of the work will be used to obtain the final temperature. The definition of work (Equation 2.7) is

$$W = -\int_{V_1}^{V_2} P_E \, dV$$

Since the piston expands at constant pressure, the above relationship becomes

$$W = -P_E \left(V_2 - V_1\right)$$

From the steam tables

$$\hat{v}_1 = 0.02641 \left[\frac{\text{m}^3}{\text{kg}}\right] \qquad (10 \text{ MPa}, 400 \text{ }^{\text{o}}\text{C})$$

$$V_1 = m_1 \hat{v}_1 = (3 \text{ kg})\left(0.02641 \left[\frac{\text{m}^3}{\text{kg}}\right]\right) = 0.07923 \left[\text{m}^3\right]$$

Now V_2 and v_2 are found as follows

$$V_2 = V_1 - \frac{W}{P_E} = 0.07923 \text{ m}^3 - \frac{-748740 \text{ J}}{2.0 \times 10^6 \text{ Pa}} = 0.4536 \left[\text{m}^3\right]$$

$$\hat{v}_2 = \frac{V_2}{m_2} = \frac{0.4536 \left[\text{m}^3\right]}{3 \left[\text{kg}\right]} = 0.1512 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

Since $\hat{v}_2$ and P_2 are known, state 2 is constrained. From the steam tables:

$$\boxed{T_2 = 400 \left[{}^{\text{o}}\text{C}\right]} \qquad \left(20 \text{ bar}, 0.1512 \left[\frac{\text{m}^3}{\text{kg}}\right]\right)$$

Now ΔU will be evaluated, which is necessary for calculating Q. From the steam tables:

$$\hat{u}_2 = 2945.2\left[\frac{\text{kJ}}{\text{kg}}\right] \qquad \left(20\text{ bar}, 0.1512\left[\frac{\text{m}^3}{\text{kg}}\right]\right)$$

$$\hat{u}_1 = 2832.4\left[\frac{\text{kJ}}{\text{kg}}\right] \qquad \left(100\text{ bar}, 400\,^{\circ}\text{C}\right)$$

$$\Delta U = m_1\left(\hat{u}_2 - \hat{u}_1\right) = \left(3\left[\text{kg}\right]\right)\left(2945.2\left[\frac{\text{kJ}}{\text{kg}}\right] - 2832.4\left[\frac{\text{kJ}}{\text{kg}}\right]\right) = 338.4\left[\text{kJ}\right]$$

Substituting the values of ΔU and W into the energy equation allows calculation of Q

$$Q = \Delta U - W$$

$$Q = 338400\,[\text{J}] - \left(-748740\left[\text{J}\right]\right) = 1.09\times 10^6\,\left[\text{J}\right]$$

2.14

In a reversible process, the system is never out of equilibrium by more than an infinitesimal amount. In this process the gas is initially at 2 bar, and it expands against a constant pressure of 1 bar. Therefore, a finite mechanical driving force exists, and the process is irreversible.

To solve for the final temperature of the system, the energy balance will be written. The piston-cylinder assembly is well-insulated, so the process can be assumed adiabatic. Furthermore, potential and kinetic energy effects can be neglected. The energy balance simplifies to

$$\Delta U = W$$

Conservation of mass requires

$$n_1 = n_2$$

Let $n = n_1 = n_2$

The above energy balance can be rewritten as

$$n\int_{T_1}^{T_2} c_v dT = -\int_{V_1}^{V_2} P_E dV$$

Since c_v and P_E are constant:

$$nc_v\left(T_2 - T_1\right) = -P_E\left(V_2 - V_1\right)$$

V_2 and T_1 can be rewritten using the ideal gas law

$$V_2 = \frac{nRT_2}{P_2}$$

$$T_1 = \frac{P_1V_1}{nR}$$

Substituting these expressions into the energy balance, realizing that $P_E = P_2$, and simplifying the equation gives

$$T_2 = \frac{\left(P_2 + \frac{5}{2}P_1\right)V_1}{\frac{7}{2}nR}$$

Using the following values