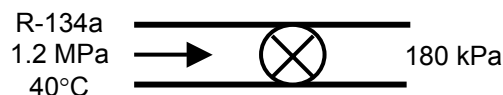---

Review Problems

8-95 Refrigerant-134a is expanded adiabatically in an expansion valve. The work potential of R-134a at the inlet, the exergy destruction, and the second-law efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis (*a*) The properties of the refrigerant at the inlet and exit of the valve and at dead state are (Tables A-11 through A-13)

$$P_1 = 1.2 \text{ MPa} \left.\right\} \begin{array}{l} h_1 = 108.23 \text{ kJ/kg} \\ T_1 = 40°C \quad s_1 = 0.39424 \text{ kJ/kg.K} \end{array}$$

$$\left. \begin{array}{l} P_2 = 180 \text{ kPa} \\ h_2 = h_1 = 108.23 \text{ kJ/kg} \end{array} \right\} s_2 = 0.42271 \text{ kJ/kg.K}$$

$$P_0 = 100 \text{ kPa} \left.\right\} \begin{array}{l} h_0 = 272.17 \text{ kJ/kg} \\ T_0 = 20°C \quad s_0 = 1.0918 \text{ kJ/kg.K} \end{array}$$

R-134a
1.2 MPa $\longrightarrow$ $\otimes$ 180 kPa
40°C

The specific exergy of the refrigerant at the inlet and exit of the valve are

$$\psi_1 = h_1 - h_0 - T_0(s_1 - s_0) = (108.23 - 272.17)\text{kJ/kg} - (20 + 273.15 \text{ K})(0.39424 - 1.0918)\text{kJ/kg.K} = \textbf{40.55 kJ/kg}$$

$$\psi_2 = h_2 - h_0 - T_0(s_2 - s_0) = (108.23 - 272.17)\text{kJ/kg} - (20 + 273.15 \text{ K})(0.42271 - 1.0918 \text{ kJ/kg.K} = 32.20 \text{ kJ/kg}$$

(*b*) The exergy destruction is determined to be

$$x_{\text{dest}} = T_0(s_2 - s_1) = (20 + 273.15 \text{ K})(0.42271 - 0.39424)\text{kJ/kg.K} = \textbf{8.34 kJ/kg}$$

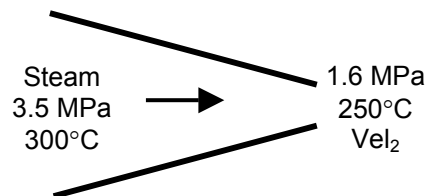(*c*) The second-law efficiency for this process may be determined from

$$\eta_{\text{II}} = \frac{\psi_2}{\psi_1} = \frac{32.20 \text{ kJ/kg}}{40.55 \text{ kJ/kg}} = \textbf{0.794}$$

8-96 Steam is accelerated in an adiabatic nozzle. The exit velocity, the rate of exergy destruction, and the second-law efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Potential energy changes are negligible.

Analysis (*a*) The properties of the steam at the inlet and exit of the turbine and at the dead state are (Tables A-4 through A-6)

$$P_1 = 3.5 \text{ MPa} \left. \right\} \begin{array}{l} h_1 = 2978.4 \text{ kJ/kg} \\ T_1 = 300°C \end{array} \left. \right\} s_1 = 6.4484 \text{ kJ/kg.K}$$

$$P_2 = 1.6 \text{ kPa} \left. \right\} \begin{array}{l} h_2 = 2919.9 \text{ kJ/kg} \\ T_2 = 250°C \end{array} \left. \right\} s_2 = 6.6753 \text{ kJ/kg.K}$$

$$T_0 = 18°C \left. \right\} \begin{array}{l} h_0 = 75.54 \text{ kJ/kg} \\ x = 0 \end{array} \left. \right\} s_0 = 0.2678 \text{ kJ/kg.K}$$

Steam
3.5 MPa
300°C

1.6 MPa
250°C
Vel$_2$

The exit velocity is determined from an energy balance on the nozzle

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$2978.4 \text{ kJ/kg} + \frac{(0 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = 2919.9 \text{ kJ/kg} + \frac{V_2^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)$$

$$V_2 = \textbf{342.0 m/s}$$

(*b*) The rate of exergy destruction is the exergy decrease of the steam in the nozzle

$$\dot{X}_{\text{dest}} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} - T_0(s_2 - s_1)\right]$$

$$= (0.4 \text{ kg/s})\left[\begin{array}{l}(2919.9 - 2978.4)\text{kJ/kg} + \frac{(342 \text{ m/s})^2 - 0}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) \\ -(291 \text{ K})(6.6753 - 6.4484)\text{kJ/kg.K}\end{array}\right]$$

$$= \textbf{26.41 kW}$$

(*c*) The exergy of the refrigerant at the inlet is

$$\dot{X}_1 = \dot{m}\left[h_1 - h_0 + \frac{V_1^2}{2} - T_0(s_1 - s_0)\right]$$

$$= (0.4 \text{ kg/s})\left[(2978.4 - 75.54) \text{ kJ/kg} + 0 - (291 \text{ K})(6.4484 - 0.2678)\text{kJ/kg.K}\right]$$

$$= 441.72 \text{ kW}$$

The second-law efficiency for this device may be defined as the exergy output divided by the exergy input:

$$\eta_{\text{II}} = \frac{\dot{X}_2}{\dot{X}_1} = 1 - \frac{\dot{X}_{\text{dest}}}{\dot{X}_1} = 1 - \frac{26.41 \text{ kW}}{441.72 \text{ kW}} = \textbf{0.940}$$

8-97 An electrical radiator is placed in a room and it is turned on for a period of time. The time period for which the heater was on, the exergy destruction, and the second-law efficiency are to be determined.

Assumptions **1** Kinetic and potential energy changes are negligible. **2** Air is an ideal gas with constant specific heats. **3** The room is well-sealed. **4** Standard atmospheric pressure of 101.3 kPa is assumed.

Properties The properties of air at room temperature are $R = 0.287$ kPa.m³/kg.K, $c_p = 1.005$ kJ/kg.K, $c_v = 0.718$ kJ/kg.K (Table A-2). The properties of oil are given to be $\rho = 950$ kg/m³, $c_{oil} = 2.2$ kJ/kg.K.

Analysis (*a*) The masses of air and oil are

$$m_a = \frac{P_1 V}{RT_1} = \frac{(101.3\,\text{kPa})(50\,\text{m}^3)}{(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(10+273\,\text{K})} = 62.36\,\text{kg}$$

$$m_{oil} = \rho_{oil} V_{oil} = (950\,\text{kg/m}^3)(0.030\,\text{m}^3) = 28.50\,\text{kg}$$

An energy balance on the system can be used to determine time period for which the heater was kept on

$$(\dot{W}_{in} - \dot{Q}_{out})\Delta t = \left[mc_v(T_2 - T_1)\right]_a + \left[mc(T_2 - T_1)\right]_{oil}$$

$$(1.8 - 0.35\,\text{kW})\Delta t = \left[(62.36\,\text{kg})(0.718\,\text{kJ/kg.°C})(20-10)\text{°C}\right] + \left[(28.50\,\text{kg})(2.2\,\text{kJ/kg.°C})(50-10)\text{°C}\right]$$

$$\Delta t = \mathbf{2038\ s} = \mathbf{34\ min}$$

(*b*) The pressure of the air at the final state is

$$P_{a2} = \frac{m_a RT_{a2}}{V} = \frac{(62.36\,\text{kg})(0.287\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(20+273\,\text{K})}{50\,\text{m}^3} = 104.9\,\text{kPa}$$

The amount of heat transfer to the surroundings is

$$Q_{out} = \dot{Q}_{out}\Delta t = (0.35\,\text{kJ/s})(2038\,\text{s}) = 713.5\,\text{kJ}$$

The entropy generation is the sum of the entropy changes of air, oil, and the surroundings

$$\Delta S_a = m\left[c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}\right]$$

$$= (62.36\,\text{kg})\left[(1.005\,\text{kJ/kg.K})\ln\frac{(20+273)\,\text{K}}{(10+273)\,\text{K}} - (0.287\,\text{kJ/kg.K})\ln\frac{104.9\,\text{kPa}}{101.3\,\text{kPa}}\right]$$

$$= 1.5548\,\text{kJ/K}$$

$$\Delta S_{oil} = mc\ln\frac{T_2}{T_1} = (28.50\,\text{kg})(2.2\,\text{kJ/kg.K})\ln\frac{(50+273)\,\text{K}}{(10+273)\,\text{K}} = 8.2893\,\text{kJ/K}$$

$$\Delta S_{surr} = \frac{Q_{out}}{T_{surr}} = \frac{713.5\,\text{kJ}}{(10+273)\,\text{K}} = 2.521\,\text{kJ/K}$$

$$S_{gen} = \Delta S_a + \Delta S_{oil} + \Delta S_{surr} = 1.5548 + 8.2893 + 2.521 = 12.365\,\text{kJ/K}$$

The exergy destruction is determined from

$$X_{dest} = T_0 S_{gen} = (10+273\,\text{K})(12.365\,\text{kJ/K}) = \mathbf{3500\ kJ}$$

(*c*) The second-law efficiency may be defined in this case as the ratio of the exergy recovered to the exergy input. That is,
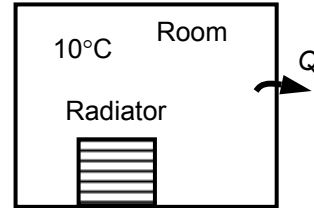
$$X_{a,2} = m\left[c_v(T_2 - T_1)\right] - T_0\Delta S_a$$

$$= (62.36\,\text{kg})\left[(0.718\,\text{kJ/kg.°C})(20\text{-}10)\text{°C}\right] - (10+273\,\text{K})(1.5548\,\text{kJ/K}) = 7.729\,\text{kJ}$$

$$X_{oil,2} = m\left[C(T_2 - T_1)\right] - T_0\Delta S_a$$

$$= (28.50\,\text{kg})\left[(2.2\,\text{kJ/kg.°C})(50\text{-}10)\text{°C}\right] - (10+273\,\text{K})(8.2893\,\text{kJ/K}) = 162.13\,\text{kJ}$$

$$\eta_{II} = \frac{X_{recovered}}{X_{supplied}} = \frac{X_{a,2} + X_{oil,2}}{\dot{W}_{in}\Delta t} = \frac{(7.729 + 162.13)\,\text{kJ}}{(1.8\,\text{kJ/s})(2038\,\text{s})} = \mathbf{0.046} = \mathbf{4.6\%}$$
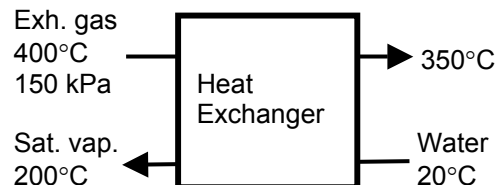
8-98 Hot exhaust gases leaving an internal combustion engine is to be used to obtain saturated steam in an adiabatic heat exchanger. The rate at which the steam is obtained, the rate of exergy destruction, and the second-law efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Air properties are used for exhaust gases. **4** Pressure drops in the heat exchanger are negligible.

Properties The gas constant of air is $R = 0.287$ kJkg.K. The specific heat of air at the average temperature of exhaust gases (650 K) is $c_p = 1.063$ kJ/kg.K (Table A-2).

Analysis (*a*) We denote the inlet and exit states of exhaust gases by (1) and (2) and that of the water by (3) and (4). The properties of water are (Table A-4)

$$\left. \begin{array}{l} T_3 = 20°C \\ x_3 = 0 \end{array} \right| \begin{array}{l} h_3 = 83.91 \, \text{kJ/kg} \\ s_3 = 0.29649 \, \text{kJ/kg.K} \end{array}$$

$$\left. \begin{array}{l} T_4 = 200°C \\ x_4 = 1 \end{array} \right| \begin{array}{l} h_4 = 2792.0 \, \text{kJ/kg} \\ s_4 = 6.4302 \, \text{kJ/kg.K} \end{array}$$

Exh. gas
400°C
150 kPa

Heat
Exchanger

350°C

Sat. vap.
200°C

Water
20°C

An energy balance on the heat exchanger gives

$$\dot{m}_a h_1 + \dot{m}_w h_3 = \dot{m}_a h_2 + \dot{m}_w h_4$$
$$\dot{m}_a c_p (T_1 - T_2) = \dot{m}_w (h_4 - h_3)$$
$$(0.8 \, \text{kg/s})(1.063 \, \text{kJ/kg°C})(400 - 350)°C = \dot{m}_w (2792.0 - 83.91) \text{kJ/kg}$$
$$\dot{m}_w = \textbf{0.01570 kg/s}$$

(*b*) The specific exergy changes of each stream as it flows in the heat exchanger is

$$\Delta s_a = c_p \ln \frac{T_2}{T_1} = (0.8 \, \text{kg/s})(1.063 \, \text{kJ/kg.K}) \ln \frac{(350 + 273) \, \text{K}}{(400 + 273) \, \text{K}} = -0.08206 \, \text{kJ/kg.K}$$

$$\begin{aligned} \Delta \psi_a &= c_p (T_2 - T_1) - T_0 \Delta s_a \\ &= (1.063 \, \text{kJ/kg.°C})(350 - 400)°C - (20 + 273 \, \text{K})(-0.08206 \, \text{kJ/kg.K}) \\ &= -29.106 \, \text{kJ/kg} \end{aligned}$$

$$\begin{aligned} \Delta \psi_w &= h_4 - h_3 - T_0 (s_4 - s_3) \\ &= (2792.0 - 83.91) \text{kJ/kg} - (20 + 273 \, \text{K})(6.4302 - 0.29649) \text{kJ/kg.K} \\ &= 910.913 \, \text{kJ/kg} \end{aligned}$$

The exergy destruction is determined from an exergy balance on the heat exchanger to be

$$-\dot{X}_{\text{dest}} = \dot{m}_a \Delta \psi_a + \dot{m}_w \Delta \psi_w = (0.8 \, \text{kg/s})(-29.106 \, \text{kJ/kg}) + (0.01570 \, \text{kg/s})(910.913) \text{kJ/kg} = -8.98 \, \text{kW}$$

or

$$\dot{X}_{\text{dest}} = \textbf{8.98 kW}$$

(*c*) The second-law efficiency for a heat exchanger may be defined as the exergy increase of the cold fluid divided by the exergy decrease of the hot fluid. That is,

$$\eta_{\text{II}} = \frac{\dot{m}_w \Delta \psi_w}{-\dot{m}_a \Delta \psi_a} = \frac{(0.01570 \, \text{kg/s})(910.913 \, \text{kJ/kg})}{-(0.8 \, \text{kg/s})(-29.106 \, \text{kJ/kg})} = \textbf{0.614}$$

8-99 The inner and outer surfaces of a brick wall are maintained at specified temperatures. The rate of exergy destruction is to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values. **2** The environment temperature is given to be $T_0 = 0°C$.

Analysis We take the wall to be the system, which is a closed system. Under steady conditions, the rate form of the entropy balance for the wall simplifies to

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy} \\ \text{generation}}} = \underbrace{\Delta \dot{S}_{system}}_{\substack{\text{Rate of change} \\ \text{of entropy}}}^{\nearrow 0} = 0$$

$$\frac{\dot{Q}_{in}}{T_{b,in}} - \frac{\dot{Q}_{out}}{T_{b,out}} + \dot{S}_{gen,wall} = 0$$

$$\frac{900\text{ W}}{293\text{ K}} - \frac{900\text{ W}}{278\text{ K}} + \dot{S}_{gen,wall} = 0 \quad \rightarrow \quad \dot{S}_{gen,wall} = 0.166\text{ W/K}$$
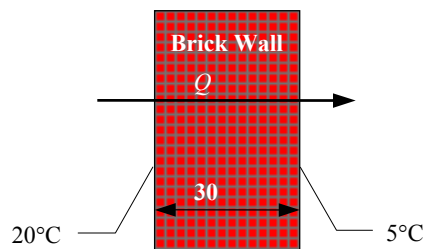
The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$,

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} = (273\text{ K})(0.166\text{ W/K}) = \textbf{45.3 W}$$

8-100 A 1000-W iron is left on the iron board with its base exposed to air. The rate of exergy destruction in steady operation is to be determined.

Assumptions Steady operating conditions exist.

Analysis The rate of total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes the iron and its immediate surroundings so that the boundary temperature of the extended system is 20°C at all times. It gives

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy} \\ \text{generation}}} = \underbrace{\Delta \dot{S}_{system}}_{\substack{\text{Rate of change} \\ \text{of entropy}}}^{\nearrow 0} = 0$$

$$-\frac{\dot{Q}_{out}}{T_{b,out}} + \dot{S}_{gen} = 0$$

Therefore,

$$\dot{S}_{gen} = \frac{\dot{Q}_{out}}{T_{b,out}} = \frac{\dot{Q}}{T_0} = \frac{1000\text{ W}}{293\text{ K}} = 3.413\text{ W/K}$$

The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$,

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} = (293\text{ K})(3.413\text{ W/K}) = \textbf{1000 W}$$

Discussion The rate of entropy generation within the iron can be determined by performing an entropy balance on the iron alone (it gives 2.21 W/K). Therefore, about one-third of the entropy generation and thus exergy destruction occurs within the iron. The rest occurs in the air surrounding the iron as the temperature drops from 150°C to 20°C without serving any useful purpose.

8-101 The heating of a passive solar house at night is to be assisted by solar heated water. The amount of heating this water will provide to the house at night and the exergy destruction during this heat transfer process are to be determined.

Assumptions **1** Water is an incompressible substance with constant specific heats. **2** The energy stored in the glass containers themselves is negligible relative to the energy stored in water. **3** The house is maintained at 22°C at all times. **4** The outdoor temperature is given to be 5°C.

Properties The density and specific heat of water at room temperature are $\rho = 997$ kg/m^3 and $c = 4.18$ kJ/kg·°C (Table A-3).

Analysis The total mass of water is

$$m_w = \rho V = \left(997 \text{ kg/m}^3\right)\left(0.350 \text{ m}^3\right) = 348.95 \text{ kg}$$

The amount of heat this water storage system can provide is determined from an energy balance on the 350-L water storage system

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$-Q_{out} = \Delta U_{system} = mc(T_2 - T_1)_{water}$$

Substituting,

$$Q_{out} = (348.95 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{°C})(45 - 22)\text{°C} = \textbf{33,548 kJ}$$

The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the water and its immediate surroundings so that the boundary temperature of the extended system is the environment temperature at all times. It gives

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$-\frac{Q_{out}}{T_{b,out}} + S_{gen} = \Delta S_{water}$$

Substituting,

$$S_{gen} = \Delta S_{water} + \frac{Q_{out}}{T_{b,out}} = \left(mc \ln \frac{T_2}{T_1}\right)_{water} + \frac{Q_{out}}{T_{room}}$$

$$= \left(348.95 \text{ kg}\right)\left(4.18 \text{ kJ/kg} \cdot \text{K}\right)\ln \frac{295 \text{ K}}{318 \text{ K}} + \frac{33,548 \text{ kJ}}{295 \text{ K}}$$

$$= 4.215 \text{ kJ/K}$$

The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$,

$$X_{destroyed} = T_0 S_{gen} = (278 \text{ K})(4.215 \text{ kJ/K}) = \textbf{1172 kJ}$$
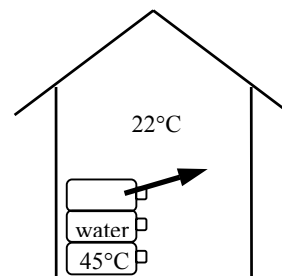
8-102 The inner and outer surfaces of a window glass are maintained at specified temperatures. The amount of heat loss and the amount of exergy destruction in 5 h are to be determined

Assumptions Steady operating conditions exist since the surface temperatures of the glass remain constant at the specified values.

Analysis We take the glass to be the system, which is a closed system. The amount of heat loss is determined from
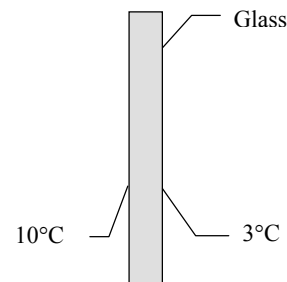
$$Q = \dot{Q}\Delta t = (3.2 \text{ kJ/s})(5 \times 3600 \text{ s}) = \textbf{57,600 kJ}$$

Under steady conditions, the rate form of the entropy balance for the glass simplifies to

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy} \\ \text{generation}}} = \underbrace{\Delta \dot{S}_{system}}_{\substack{\text{Rate of change} \\ \text{of entropy}}}^{\nearrow 0} = 0$$

$$\frac{\dot{Q}_{in}}{T_{b,in}} - \frac{\dot{Q}_{out}}{T_{b,out}} + \dot{S}_{gen,glass} = 0$$

$$\frac{3200 \text{ W}}{283 \text{ K}} - \frac{3200 \text{ W}}{276 \text{ K}} + \dot{S}_{gen,wall} = 0 \quad \rightarrow \quad \dot{S}_{gen,glass} = 0.2868 \text{ W/K}$$

Then the amount of entropy generation over a period of 5 h becomes

$$S_{gen,glass} = \dot{S}_{gen,glass}\Delta t = (0.2868 \text{ W/K})(5 \times 3600 \text{ s}) = 5162 \text{ J/K}$$

The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$,

$$X_{destroyed} = T_0 S_{gen} = (278 \text{ K})(5.162 \text{ kJ/K}) = \textbf{1435 kJ}$$

Discussion The total entropy generated during this process can be determined by applying the entropy balance on an *extended system* that includes the glass and its immediate surroundings on both sides so that the boundary temperature of the extended system is the room temperature on one side and the environment temperature on the other side at all times. Using this value of entropy generation will give the total exergy destroyed during the process, including the temperature gradient zones on both sides of the window.

8-103 Heat is transferred steadily to boiling water in the pan through its bottom. The inner and outer surface temperatures of the bottom of the pan are given. The rate of exergy destruction within the bottom plate is to be determined.

Assumptions Steady operating conditions exist since the surface temperatures of the pan remain constant at the specified values.

Analysis We take the bottom of the pan to be the system, which is a closed system. Under steady conditions, the rate form of the entropy balance for this system can be expressed as

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy} \\ \text{generation}}} = \underbrace{\Delta \dot{S}_{system}}_{\substack{\text{Rate of change} \\ \text{of entropy}}}^{\nearrow 0} = 0$$

$$\frac{\dot{Q}_{in}}{T_{b,in}} - \frac{\dot{Q}_{out}}{T_{b,out}} + \dot{S}_{gen,system} = 0$$

$$\frac{800 \text{ W}}{378 \text{ K}} - \frac{800 \text{ W}}{377 \text{ K}} + \dot{S}_{gen,system} = 0 \quad \rightarrow \quad \dot{S}_{gen,system} = 0.00561 \text{ W/K}$$
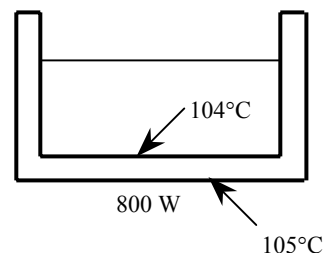
The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$,

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} = (298 \text{ K})(0.00561 \text{ W/K}) = \textbf{1.67 W}$$

8-104 A elevation, base area, and the depth of a crater lake are given. The maximum amount of electricity that can be generated by a hydroelectric power plant is to be determined.
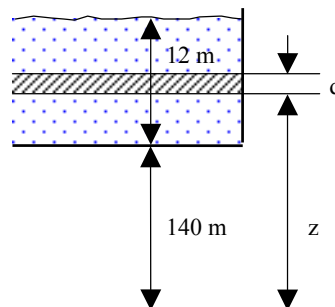
Assumptions The evaporation of water from the lake is negligible.

Analysis The exergy or work potential of the water is the potential energy it possesses relative to the ground level,

$$\text{Exergy} = \text{PE} = mgh$$

Therefore,

$$\text{Exergy} = PE = \int dPE = \int gz\,dm = \int gz(\rho A\,dz)$$

$$= \rho Ag \int_{z_1}^{z_2} z\,dz = \rho Ag(z_2^2 - z_1^2)/2$$

$$= 0.5(1000\,\text{kg/m}^3)(2 \times 10^4\,\text{m}^2)(9.81\,\text{m/s}^2)$$

$$\times \left((152\,\text{m})^2 - (140\,\text{m}^2)\right)\left(\frac{1\,\text{h}}{3600\,\text{s}}\right)\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right)$$

$$= \mathbf{9.55 \times 10^4\ kWh}$$

8-105E The 2nd-law efficiency of a refrigerator and the refrigeration rate are given. The power input to the refrigerator is to be determined.

Analysis From the definition of the second law efficiency, the COP of the refrigerator is determined to be

$$\text{COP}_{R,\text{rev}} = \frac{1}{T_H/T_L - 1} = \frac{1}{535/495 - 1} = 12.375$$

$$\eta_{II} = \frac{\text{COP}_R}{\text{COP}_{R,\text{rev}}} \longrightarrow \text{COP}_R = \eta_{II}\text{COP}_{R,\text{rev}} = 0.45 \times 12.375 = 5.57$$

Thus the power input is

$$\dot{W}_{in} = \frac{\dot{Q}_L}{\text{COP}_R} = \frac{200\,\text{Btu/min}}{5.57}\left(\frac{1\,\text{hp}}{42.41\,\text{Btu/min}}\right) = \mathbf{0.85\ hp}$$
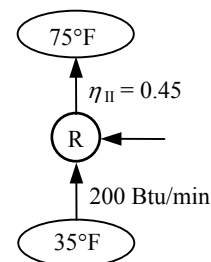
8-106 Writing energy and entropy balances, a relation for the reversible work is to be obtained for a closed system that exchanges heat with surroundings at T_0 in the amount of Q_0 as well as a heat reservoir at temperature T_R in the amount Q_R.

Assumptions Kinetic and potential changes are negligible.

Analysis We take the direction of heat transfers to be to the system (heat input) and the direction of work transfer to be from the system (work output). The result obtained is still general since quantities wit opposite directions can be handled the same way by using negative signs. The energy and entropy balances for this stationary closed system can be expressed as

Energy balance: $E_{in} - E_{out} = \Delta E_{system} \rightarrow Q_0 + Q_R - W = U_2 - U_1 \longrightarrow W = U_1 - U_2 + Q_0 + Q_R$ (1)

Entropy balance: $S_{in} - S_{out} + S_{gen} = \Delta S_{system} \rightarrow S_{gen} = (S_2 - S_1) + \dfrac{-Q_R}{T_R} + \dfrac{-Q_0}{T_0}$ (2)

Solving for Q_0 from (2) and substituting in (1) yields

$$W = (U_1 - U_2) - T_0(S_1 - S_2) - Q_R\left(1 - \frac{T_0}{T_R}\right) - T_0 S_{gen}$$

The useful work relation for a closed system is obtained from

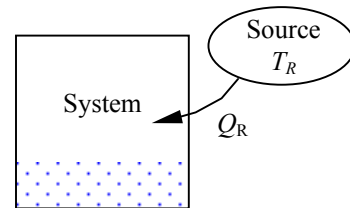$$W_u = W - W_{surr}$$

$$= (U_1 - U_2) - T_0(S_1 - S_2) - Q_R\left(1 - \frac{T_0}{T_R}\right) - T_0 S_{gen} - P_0(V_2 - V_1)$$

Then the reversible work relation is obtained by substituting $S_{gen} = 0$,

$$W_{rev} = (U_1 - U_2) - T_0(S_1 - S_2) + P_0(V_1 - V_2) - Q_R\left(1 - \frac{T_0}{T_R}\right)$$

A positive result for W_{rev} indicates work output, and a negative result work input. Also, the Q_R is a positive quantity for heat transfer to the system, and a negative quantity for heat transfer from the system.

8-107 Writing energy and entropy balances, a relation for the reversible work is to be obtained for a steady-flow system that exchanges heat with surroundings at T_0 at a rate of $\dot{Q}_0$ as well as a heat reservoir at temperature T_R in the amount $\dot{Q}_R$.

Analysis We take the direction of heat transfers to be to the system (heat input) and the direction of work transfer to be from the system (work output). The result obtained is still general since quantities wit opposite directions can be handled the same way by using negative signs. The energy and entropy balances for this stationary closed system can be expressed as

Energy balance: $\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system} \rightarrow \dot{E}_{in} = \dot{E}_{out}$

$$\dot{Q}_0 + \dot{Q}_R - \dot{W} = \sum \dot{m}_e (h_e + \frac{V_e^2}{2} + gz_e) - \sum \dot{m}_i (h_i + \frac{V_i^2}{2} + gz_i)$$

or $\quad \dot{W} = \sum \dot{m}_i (h_i + \frac{V_i^2}{2} + gz_i) - \sum \dot{m}_e (h_e + \frac{V_e^2}{2} + gz_e) + \dot{Q}_0 + \dot{Q}_R \quad$ (1)

Entropy balance: $\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta\dot{S}_{system} \rightarrow \dot{S}_{gen} = \dot{S}_{out} - \dot{S}_{in}$

$$\dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i + \frac{-\dot{Q}_R}{T_R} + \frac{-\dot{Q}_0}{T_0} \qquad (2)$$

Solving for $\dot{Q}_0$ from (2) and substituting in (1) yields

$$\dot{W} = \sum \dot{m}_i (h_i + \frac{V_i^2}{2} + gz_i - T_0 s_i) - \sum \dot{m}_e (h_e + \frac{V_e^2}{2} + gz_e - T_0 s_e) - T_0 \dot{S}_{gen} - \dot{Q}_R \left(1 - \frac{T_0}{T_R}\right)$$

Then the reversible work relation is obtained by substituting $S_{gen} = 0$,

$$\dot{W}_{rev} = \sum \dot{m}_i (h_i + \frac{V_i^2}{2} + gz_i - T_0 s_i) - \sum \dot{m}_e (h_e + \frac{V_e^2}{2} + gz_e - T_0 s_e) - \dot{Q}_R \left(1 - \frac{T_0}{T_R}\right)$$

A positive result for W_{rev} indicates work output, and a negative result work input. Also, the Q_R is a positive quantity for heat transfer to the system, and a negative quantity for heat transfer from the system.
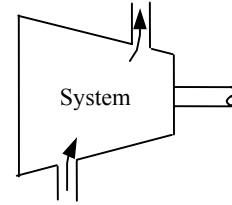
8-108 Writing energy and entropy balances, a relation for the reversible work is to be obtained for a uniform-flow system that exchanges heat with surroundings at T_0 in the amount of Q_0 as well as a heat reservoir at temperature T_R in the amount Q_R.

Assumptions Kinetic and potential changes are negligible.

Analysis We take the direction of heat transfers to be to the system (heat input) and the direction of work transfer to be from the system (work output). The result obtained is still general since quantities wit opposite directions can be handled the same way by using negative signs. The energy and entropy balances for this stationary closed system can be expressed as

Energy balance: $E_{in} - E_{out} = \Delta E_{system}$

$$Q_0 + Q_R - W = \sum m_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) - \sum m_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) + (U_2 - U_1)_{cv}$$
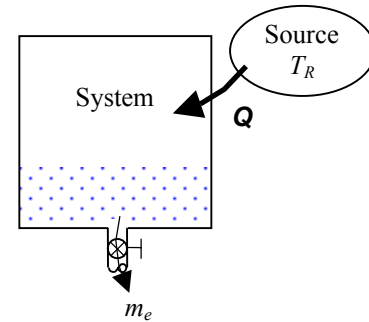
or, $\qquad W = \sum m_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum m_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) - (U_2 - U_1)_{cv} + Q_0 + Q_R \quad (1)$

Entropy balance: $S_{in} - S_{out} + S_{gen} = \Delta S_{system}$

$$S_{gen} = (S_2 - S_1)_{cv} + \sum m_e s_e - \sum m_i s_i + \frac{-Q_R}{T_R} + \frac{-Q_0}{T_0} \quad (2)$$

Solving for Q_0 from (2) and substituting in (1) yields

$$W = \sum m_i \left(h_i + \frac{V_i^2}{2} + gz_i - T_0 s_i \right) - \sum m_e \left(h_e + \frac{V_e^2}{2} + gz_e - T_0 s_e \right)$$

$$+ \left[(U_1 - U_2) - T_0 (S_1 - S_2) \right]_{cv} - T_0 S_{gen} - Q_R \left(1 - \frac{T_0}{T_R} \right)$$

The useful work relation for a closed system is obtained from

$$W_u = W - W_{surr} = \sum m_i \left(h_i + \frac{V_i^2}{2} + gz_i - T_0 s_i \right) - \sum m_e \left(h_e + \frac{V_e^2}{2} + gz_e - T_0 s_e \right)$$

$$+ \left[(U_1 - U_2) - T_0 (S_1 - S_2) \right]_{cv} - T_0 S_{gen} - Q_R \left(1 - \frac{T_0}{T_R} \right) - P_0 (V_2 - V_1)$$

Then the reversible work relation is obtained by substituting $S_{gen} = 0$,

$$W_{rev} = \sum m_i \left(h_i + \frac{V_i^2}{2} + gz_i - T_0 s_i \right) - \sum m_e \left(h_e + \frac{V_e^2}{2} + gz_e - T_0 s_e \right)$$

$$+ \left[(U_1 - U_2) - T_0 (S_1 - S_2) + P_0 (V_1 - V_2) \right]_{cv} - Q_R \left(1 - \frac{T_0}{T_R} \right)$$

A positive result for W_{rev} indicates work output, and a negative result work input. Also, the Q_R is a positive quantity for heat transfer to the system, and a negative quantity for heat transfer from the system.

8-109 An electric resistance heater is immersed in water. The time it will take for the electric heater to raise the water temperature to a specified temperature, the minimum work input, and the exergy destroyed during this process are to be determined.

Assumptions **1** Water is an incompressible substance with constant specific heats. **2** The energy stored in the container itself and the heater is negligible. **3** Heat loss from the container is negligible. **4** The environment temperature is given to be $T_0 = 20°C$.
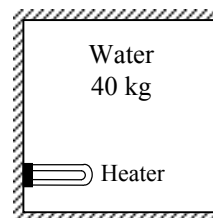
Properties The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3).

Analysis Taking the water in the container as the system, which is a closed system, the energy balance can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$W_{e,in} = (\Delta U)_{water}$$

$$\dot{W}_{e,in} \Delta t = mc(T_2 - T_1)_{water}$$

Substituting, $(800$ J/s$)\Delta t = (40$ kg$)(4180$ J/kg·°C$)(80 - 20)°C$

Solving for Δt gives

$$\Delta t = \textbf{12,544 s = 209.1 min = 3.484 h}$$

Again we take the water in the tank to be the system. Noting that no heat or mass crosses the boundaries of this system and the energy and entropy contents of the heater are negligible, the entropy balance for it can be expressed as

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$0 + S_{gen} = \Delta S_{water}$$

Therefore, the entropy generated during this process is

$$S_{gen} = \Delta S_{water} = mc \ln \frac{T_2}{T_1} = (40 \text{ kg})(4.184 \text{ kJ/kg} \cdot \text{K}) \ln \frac{353 \text{ K}}{293 \text{ K}} = \textbf{31.18 kJ/K}$$

The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$,

$$X_{destroyed} = T_0 S_{gen} = (293 \text{ K})(31.18 \text{ kJ/K}) = \textbf{9136 kJ}$$

The actual work input for this process is

$$W_{act,in} = \dot{W}_{act,in} \Delta t = (0.8 \text{ kJ/s})(12,552 \text{ s}) = 10,042 \text{ kJ}$$

Then the reversible (or minimum required)work input becomes

$$W_{rev,in} = W_{act,in} - X_{destroyed} = 10,042 - 9136 = \textbf{906 kJ}$$

8-110 A hot water pipe at a specified temperature is losing heat to the surrounding air at a specified rate. The rate at which the work potential is wasted during this process is to be determined.

Assumptions Steady operating conditions exist.

Analysis We take the air in the vicinity of the pipe (excluding the pipe) as our system, which is a closed system.. The system extends from the outer surface of the pipe to a distance at which the temperature drops to the surroundings temperature. In steady operation, the rate form of the entropy balance for this system can be expressed as

$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy} \\ \text{generation}}} = \underbrace{\Delta \dot{S}_{system}}_{\substack{\text{Rate of change} \\ \text{of entropy}}}^{\nearrow 0} = 0$$

$$\frac{\dot{Q}_{in}}{T_{b,in}} - \frac{\dot{Q}_{out}}{T_{b,out}} + \dot{S}_{gen,system} = 0$$

$$\frac{45 \text{ W}}{353 \text{ K}} - \frac{45 \text{ W}}{278 \text{ K}} + \dot{S}_{gen,system} = 0 \quad \rightarrow \quad \dot{S}_{gen,system} = 0.0344 \text{ W/K}$$
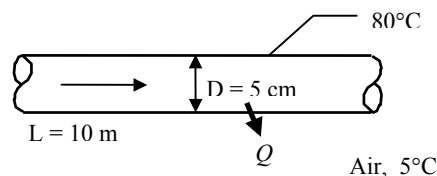
The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$,

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} = (278 \text{ K})(0.0344 \text{ W/K}) = \textbf{9.56 W}$$

8-111 Two rigid tanks that contain water at different states are connected by a valve. The valve is opened and steam flows from tank A to tank B until the pressure in tank A drops to a specified value. Tank B loses heat to the surroundings. The final temperature in each tank and the work potential wasted during this process are to be determined.

Assumptions **1** Tank A is insulated and thus heat transfer is negligible. **2** The water that remains in tank A undergoes a reversible adiabatic process. **3** The thermal energy stored in the tanks themselves is negligible. **4** The system is stationary and thus kinetic and potential energy changes are negligible. **5** There are no work interactions.

Analysis (a) The steam in tank A undergoes a reversible, adiabatic process, and thus $s_2 = s_1$. From the steam tables (Tables A-4 through A-6),

Tank A :

$$P_1 = 400 \text{ kPa} \atop x_1 = 0.8 \left.\begin{cases} \boldsymbol{v}_{1,A} = \boldsymbol{v}_f + x_1 \boldsymbol{v}_{fg} = 0.001084 + (0.8)(0.46242 - 0.001084) = 0.37015 \text{ m}^3/\text{kg} \\ u_{1,A} = u_f + x_1 u_{fg} = 604.22 + (0.8)(1948.9) = 2163.3 \text{ kJ/kg} \\ s_{1,A} = s_f + x_1 s_{fg} = 1.7765 + (0.8)(5.1191) = 5.8717 \text{ kJ/kg} \cdot \text{K} \end{cases}\right.$$

$$T_{2,A} = T_{sat@300kPa} = \mathbf{133.52°C}$$

$$\begin{matrix} P_2 = 300 \text{ kPa} \\ s_2 = s_1 \\ (\text{sat. mixture}) \end{matrix} \left.\begin{cases} x_{2,A} = \dfrac{s_{2,A} - s_f}{s_{fg}} = \dfrac{5.8717 - 1.6717}{5.3200} = 0.7895 \\ \boldsymbol{v}_{2,A} = \boldsymbol{v}_f + x_{2,A} \boldsymbol{v}_{fg} = 0.001073 + (0.7895)(0.60582 - 0.001073) = 0.47850 \text{ m}^3/\text{kg} \\ u_{2,A} = u_f + x_{2,A} u_{fg} = 561.11 + (0.7895)(1982.1 \text{ kJ/kg}) = 2125.9 \text{ kJ/kg} \end{cases}\right.$$

Tank B :

$$P_1 = 200 \text{ kPa} \atop T_1 = 250°C \left.\begin{cases} \boldsymbol{v}_{1,B} = 1.1989 \text{ m}^3/\text{kg} \\ u_{1,B} = 2731.4 \text{ kJ/kg} \\ s_{1,B} = 7.7100 \text{ kJ/kg} \cdot \text{K} \end{cases}\right.$$

The initial and the final masses in tank A are

$$m_{1,A} = \frac{\boldsymbol{V}_A}{\boldsymbol{v}_{1,A}} = \frac{0.2 \text{ m}^3}{0.37015 \text{ m}^3/\text{kg}} = 0.5403 \text{ kg}$$

and

$$m_{2,A} = \frac{\boldsymbol{V}_A}{\boldsymbol{v}_{2,A}} = \frac{0.2 \text{m}^3}{0.479 \text{m}^3/\text{kg}} = 0.4180 \text{ kg}$$

Thus, $0.540 - 0.418 = 0.122$ kg of mass flows into tank B. Then,

$$m_{2,B} = m_{1,B} - 0.122 = 3 + 0.122 = 3.122 \text{ kg}$$

The final specific volume of steam in tank B is determined from

$$v_{2,B} = \frac{\boldsymbol{V}_B}{m_{2,B}} = \frac{(m_1 v_1)_B}{m_{2,B}} = \frac{(3 \text{ kg})(1.1989 \text{ m}^3/\text{kg})}{3.122 \text{ m}^3} = 1.152 \text{ m}^3/\text{kg}$$
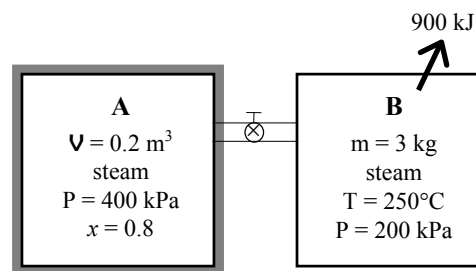
We take the entire contents of both tanks as the system, which is a closed system. The energy balance for this stationary closed system can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$-Q_{out} = \Delta U = (\Delta U)_A + (\Delta U)_B \quad (\text{since } W = KE = PE = 0)$$

$$-Q_{out} = (m_2 u_2 - m_1 u_1)_A + (m_2 u_2 - m_1 u_1)_B$$

Substituting,

900 kJ

A

$\boldsymbol{V} = 0.2 \text{ m}^3$
steam
P = 400 kPa
x = 0.8

B

m = 3 kg
steam
T = 250°C
P = 200 kPa

$$-900 = \{(0.418)(2125.9) - (0.5403)(2163.3)\} + \{(3.122)u_{2,B} - (3)(2731.4)\}$$

$$u_{2,B} = 2425.9 \text{ kJ/kg}$$

Thus,

$$\begin{array}{l} v_{2,B} = 1.152 \text{ m}^3/\text{kg} \\ u_{2,B} = 2425.9 \text{ kJ/kg} \end{array} \left| \begin{array}{l} T_{2,B} = \textbf{110.1°C} \\ s_{2,B} = 6.9772 \text{ kJ/kg} \cdot \text{K} \end{array} \right.$$

(*b*) The total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes both tanks and their immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. It gives

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_{\text{b,surr}}} + S_{\text{gen}} = \Delta S_A + \Delta S_B$$

Rearranging and substituting, the total entropy generated during this process is determined to be

$$S_{\text{gen}} = \Delta S_A + \Delta S_B + \frac{Q_{\text{out}}}{T_{\text{b,surr}}} = \left(m_2 s_2 - m_1 s_1\right)_A + \left(m_2 s_2 - m_1 s_1\right)_B + \frac{Q_{\text{out}}}{T_{\text{b,surr}}}$$

$$= \{(0.418)(5.8717) - (0.5403)(5.8717)\} + \{(3.122)(6.9772) - (3)(7.7100)\} + \frac{900 \text{ kJ}}{273 \text{ K}}$$

$$= 1.234 \text{ kJ/K}$$

The work potential wasted is equivalent to the exergy destroyed during a process, which can be determined from an exergy balance or directly from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = (273 \text{ K})(1.234 \text{ kJ/K}) = \textbf{337 kJ}$$

8-112E A cylinder initially filled with helium gas at a specified state is compressed polytropically to a specified temperature and pressure. The actual work consumed and the minimum useful work input needed are to be determined.

Assumptions **1** Helium is an ideal gas with constant specific heats. **2** The cylinder is stationary and thus the kinetic and potential energy changes are negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium. **5** The environment temperature is 70°F.

Properties The gas constant of helium is $R = 2.6805$ psia.ft^3/lbm.R $= 0.4961$ Btu/lbm.R (Table A-1E). The specific heats of helium are $c_v = 0.753$ and $c_v = 1.25$ Btu/lbm.R (Table A-2E).

Analysis (a) Helium at specified conditions can be treated as an ideal gas. The mass of helium is

$$m = \frac{P_1 V_1}{RT_1} = \frac{(25 \text{ psia})(15 \text{ ft}^3)}{(2.6805 \text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(530 \text{ R})} = 0.264 \text{ lbm}$$

The exponent n and the boundary work for this polytropic process are determined to be

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \longrightarrow V_2 = \frac{T_2}{T_1}\frac{P_1}{P_2} V_1 = \frac{(760 \text{ R})(25 \text{ psia})}{(530 \text{ R})(70 \text{ psia})}(15 \text{ ft}^3) = 7.682 \text{ ft}^3$$

$$P_2 V_2^n = P_1 V_1^n \longrightarrow \left(\frac{P_2}{P_1}\right) = \left(\frac{V_1}{V_2}\right)^n \longrightarrow \left(\frac{70}{25}\right) = \left(\frac{15}{7.682}\right)^n \longrightarrow n = 1.539$$

Then the boundary work for this polytropic process can be determined from

$$W_{b,in} = -\int_1^2 P\,dV = -\frac{P_2 V_2 - P_1 V_1}{1-n} = -\frac{mR(T_2 - T_1)}{1-n}$$

$$= -\frac{(0.264 \text{ lbm})(0.4961 \text{ Btu/lbm}\cdot\text{R})(760-530)\text{R}}{1-1.539} = 55.9 \text{ Btu}$$

Also,

$$W_{surr,in} = -P_0(V_2 - V_1) = -(14.7 \text{ psia})(7.682-15)\text{ft}^3\left(\frac{1\,\text{Btu}}{5.4039 \text{ psia}\cdot\text{ft}^3}\right) = 19.9 \text{ Btu}$$

Thus,

$$W_{u,in} = W_{b,in} - W_{surr,in} = 55.9 - 19.9 = \mathbf{36.0}\ \mathbf{Btu}$$

(*b*) We take the helium in the cylinder as the system, which is a closed system. Taking the direction of heat transfer to be from the cylinder, the energy balance for this stationary closed system can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$-Q_{out} + W_{b,in} = \Delta U = m(u_2 - u_1)$$

$$-Q_{out} = m(u_2 - u_1) - W_{b,in}$$

$$Q_{out} = W_{b,in} - mc_v(T_2 - T_1)$$

Substituting,

$$Q_{out} = 55.9 \text{ Btu} - (0.264 \text{ lbm})(0.753 \text{ Btu/lbm}\cdot\text{R})(760-530)\text{R} = 10.2 \text{ Btu}$$

The total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes the cylinder and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. It gives
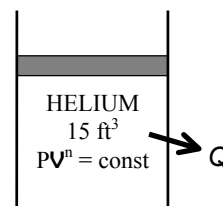
$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$-\frac{Q_{\text{out}}}{T_{\text{b,surr}}} + S_{\text{gen}} = \Delta S_{\text{sys}}$$

where the entropy change of helium is

$$\Delta S_{\text{sys}} = \Delta S_{\text{helium}} = m\left(c_{p,\text{avg}} \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1} \right)$$

$$= (0.264\text{ lbm})\left[(1.25\text{ Btu/lbm}\cdot\text{R})\ln\frac{760\text{ R}}{530\text{ R}} - (0.4961\text{ Btu/lbm}\cdot\text{R})\ln\frac{70\text{ psia}}{25\text{ psia}} \right]$$

$$= -0.0159\text{ Btu/R}$$

Rearranging and substituting, the total entropy generated during this process is determined to be

$$S_{\text{gen}} = \Delta S_{\text{helium}} + \frac{Q_{\text{out}}}{T_0} = (-0.0159\text{ Btu/R}) + \frac{10.2\text{ Btu}}{530\text{ R}} = 0.003345\text{ Btu/R}$$

The work potential wasted is equivalent to the exergy destroyed during a process, which can be determined from an exergy balance or directly from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = (530\text{ R})(0.003345\text{ Btu/R}) = 1.77\text{ Btu}$$

The minimum work with which this process could be accomplished is the reversible work input, $W_{\text{rev, in}}$. which can be determined directly from

$$W_{\text{rev,in}} = W_{\text{act,in}} - X_{\text{destroyed}} = 36.0 - 1.77 = \textbf{34.23 Btu}$$

Discussion The reversible work input, which represents the minimum work input $W_{\text{rev,in}}$ in this case can be determined from the exergy balance by setting the exergy destruction term equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer} \\ \text{by heat, work, and mass}}} - \underbrace{X_{\text{destroyed}}^{\nearrow 0\text{ (reversible)}}}_{\substack{\text{Exergy} \\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change} \\ \text{in exergy}}} \rightarrow W_{\text{rev,in}} = X_2 - X_1$$

Substituting the closed system exergy relation, the reversible work input during this process is determined to be

$$W_{\text{rev}} = (U_2 - U_1) - T_0(S_2 - S_1) + P_0(V_2 - V_1)$$

$$= (0.264\text{ lbm})(0.753\text{ Btu/lbm}\cdot\text{R})(300 - 70)°\text{F} - (530\text{ R})(-0.0159\text{ Btu/R})$$

$$+ (14.7\text{ psia})(7.682 - 15)\text{ft}^3[\text{Btu/5.4039 psia}\cdot\text{ft}^3]$$

$$= \textbf{34.24 Btu}$$