8-31 Steam and R-134a at the same states are considered. The fluid with the higher exergy content is to be identified.

Assumptions Kinetic and potential energy changes are negligible.

Analysis The properties of water at the given state and at the dead state are

Steam
1 kg
800 kPa
180°C

$$\left.\begin{array}{l} P = 800\text{ kPa} \\ T = 180°\text{C} \end{array}\right\} \begin{array}{l} u = 2594.7\text{ kJ/kg} \\ v = 0.24720\text{ m}^3\text{/kg} \quad \text{(Table A - 6)} \\ s = 6.7155\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_0 = 25°\text{C} \\ P_0 = 100\text{ kPa} \end{array}\right\} \begin{array}{l} u_0 \cong u_{f\,@\,25°\text{C}} = 104.83\text{ kJ/kg} \\ v_0 \cong v_{f\,@\,25°\text{C}} = 0.001003\text{ m}^3\text{/kg} \quad \text{(Table A - 4)} \\ s_0 \cong s_{f\,@\,25°\text{C}} = 0.3672\text{ kJ/kg}\cdot\text{K} \end{array}$$

The exergy of steam is

$$\begin{aligned} \Phi &= m\left[u - u_0 + P_0(v - v_0) - T_0(s - s_0)\right] \\ &= (1\text{ kg})\left[\begin{array}{l} (2594.7 - 104.83)\text{kJ/kg} + (100\text{ kPa})(0.24720 - 0.001003)\text{m}^3\text{/kg}\left(\dfrac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ -(298\text{ K})(6.7155 - 0.3672)\text{kJ/kg}\cdot\text{K} \end{array}\right] \\ &= \mathbf{622.7\ kJ} \end{aligned}$$

For R-134a;

R-134a
1 kg
800 kPa
180°C

$$\left.\begin{array}{l} P = 800\text{ kPa} \\ T = 180°\text{C} \end{array}\right\} \begin{array}{l} u = 386.99\text{ kJ/kg} \\ v = 0.044554\text{ m}^3\text{/kg} \quad \text{(Table A -13)} \\ s = 1.3327\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_0 = 25°\text{C} \\ P_0 = 100\text{ kPa} \end{array}\right\} \begin{array}{l} u_0 \cong u_{f\,@\,25°\text{C}} = 85.85\text{ kJ/kg} \\ v_0 \cong v_{f\,@\,25°\text{C}} = 0.0008286\text{ m}^3\text{/kg} \quad \text{(Table A -11)} \\ s_0 \cong s_{f\,@\,25°\text{C}} = 0.32432\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\begin{aligned} \Phi &= m\left[u - u_0 + P_0(v - v_0) - T_0(s - s_0)\right] \\ &= (1\text{ kg})\left[\begin{array}{l} (386.99 - 85.85)\text{kJ/kg} + (100\text{ kPa})(0.044554 - 0.0008286)\text{m}^3\text{/kg}\left(\dfrac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ -(298\text{ K})(1.3327 - 0.32432)\text{kJ/kg}\cdot\text{K} \end{array}\right] \\ &= \mathbf{5.02\ kJ} \end{aligned}$$

The steam can therefore has more work potential than the R-134a.

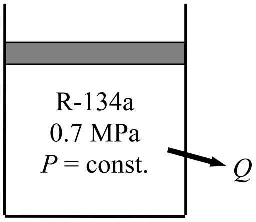
8-32 A cylinder is initially filled with R-134a at a specified state. The refrigerant is cooled and condensed at constant pressure. The exergy of the refrigerant at the initial and final states, and the exergy destroyed during this process are to be determined.

Assumptions The kinetic and potential energies are negligible.

Properties From the refrigerant tables (Tables A-11 through A-13),

$$\left.\begin{array}{l} P_1 = 0.7\text{ MPa} \\ T_1 = 60°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = 0.034875\text{ m}^3/\text{kg} \\ u_1 = 274.01\text{ kJ/kg} \\ s_1 = 1.0256\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 0.7\text{ MPa} \\ T_2 = 24°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 \cong \boldsymbol{v}_{f@24°\text{C}} = 0.0008261\text{ m}^3/\text{kg} \\ u_2 \cong u_{f@24°\text{C}} = 84.44\text{ kJ/kg} \\ s_2 \cong s_{f@24°\text{C}} = 0.31958\text{ kJ/kg}\cdot\text{K} \end{array}$$



$$\left.\begin{array}{l} P_0 = 0.1\text{ MPa} \\ T_0 = 24°\text{C} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_0 = 0.23718\text{ m}^3/\text{kg} \\ u_0 = 251.84\text{ kJ/kg} \\ s_0 = 1.1033\text{ kJ/kg}\cdot\text{K} \end{array}$$

Analysis (*a*) From the closed system exergy relation,

$$\begin{aligned} X_1 = \Phi_1 &= m\{(u_1 - u_0) - T_0(s_1 - s_0) + P_0(\boldsymbol{v}_1 - \boldsymbol{v}_0)\} \\ &= (5\text{ kg})\{(274.01 - 251.84)\text{ kJ/kg} - (297\text{ K})(1.0256 - 1.1033)\text{ kJ/kg}\cdot\text{K} \\ &\quad + (100\text{ kPa})(0.034875 - 0.23718)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)\} \\ &= \mathbf{125.1\ kJ} \end{aligned}$$

and

$$\begin{aligned} X_2 = \Phi_2 &= m\{(u_2 - u_0) - T_0(s_2 - s_0) + P_0(\boldsymbol{v}_2 - \boldsymbol{v}_0)\} \\ &= (5\text{ kg})\{(84.44 - 251.84)\text{ kJ/kg - }(297\text{ K})(0.31958 - 1.1033)\text{ kJ/kg}\cdot\text{K} \\ &\quad + (100\text{ kPa})(0.0008261 - 0.23718)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)\} \\ &= \mathbf{208.6\ kJ} \end{aligned}$$

(*b*) 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 equal to zero,

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

$$W_{\text{rev,in}} = X_2 - X_1 = 208.6 - 125.1 = 83.5\text{ kJ}$$

Noting that the process involves only boundary work, the useful work input during this process is simply the boundary work in excess of the work done by the surrounding air,

$$\begin{aligned} W_{\text{u,in}} &= W_{\text{in}} - W_{\text{surr,in}} = W_{\text{in}} - P_0(\boldsymbol{V}_1 - \boldsymbol{V}_2) = P(\boldsymbol{V}_1 - \boldsymbol{V}_2) - P_0 m(\boldsymbol{v}_1 - \boldsymbol{v}_2) \\ &= m(P - P_0)(\boldsymbol{v}_1 - \boldsymbol{v}_2) \\ &= (5\text{ kg})(700\text{ - }100\text{ kPa})(0.034875 - 0.0008261\text{ m}^3/\text{kg})\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 102.1\text{ kJ} \end{aligned}$$

Knowing both the actual useful and reversible work inputs, the exergy destruction or irreversibility that is the difference between the two is determined from its definition to be

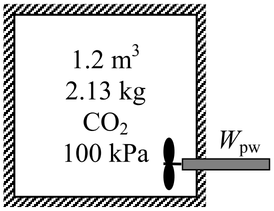
$$X_{\text{destroyed}} = I = W_{\text{u,in}} - W_{\text{rev,in}} = 102.1 - 83.5 = \mathbf{18.6\ kJ}$$

8-41 An insulated tank contains CO_2 gas at a specified pressure and volume. A paddle-wheel in the tank stirs the gas, and the pressure and temperature of CO_2 rises. The actual paddle-wheel work and the minimum paddle-wheel work by which this process can be accomplished are to be determined.

Assumptions **1** At specified conditions, CO_2 can be treated as an ideal gas with constant specific heats at the average temperature. **2** The surroundings temperature is 298 K.

Properties The gas constant of CO_2 is 0.1889 kJ/kg·K (Table A-1)

Analysis (a) The initial and final temperature of CO_2 are



$$T_1=\frac{P_1\mathbf{V}_1}{mR}=\frac{(100\,\text{kPa})(1.2\,\text{m}^3)}{(2.13\,\text{kg})(0.1889\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})}=298.2\,\text{K}$$

$$T_2=\frac{P_2\mathbf{V}_2}{mR}=\frac{(120\,\text{kPa})(1.2\,\text{m}^3)}{(2.13\,\text{kg})(0.1889\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})}=357.9\,\text{K}$$

$$T_{\text{avg}}=(T_1+T_2)/2=(298.2+357.9)/2=328\,\text{K}\longrightarrow c_{v,\text{avg}}=0.684\,\text{kJ/kg}\cdot\text{K}\ \ \text{(Table A-2}\mathit{b)}$$

The actual paddle-wheel work done is determined from the energy balance on the CO gas in the tank,

We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. The energy balance for this stationary closed system can be expressed as

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

$$W_{\text{pw,in}}=\Delta U=mc_v(T_2-T_1)$$

or

$$W_{\text{pw,in}}=(2.13\,\text{kg})(0.684\,\text{kJ/kg}\cdot\text{K})(357.9-298.2)\text{K}=\mathbf{87.0\,kJ}$$

(b) The minimum paddle-wheel work with which this process can be accomplished is the reversible work,

which can be determined from the exergy balance by setting the exergy destruction 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 for this process is determined to be

$$\begin{aligned}W_{\text{rev,in}}&=m\left[(u_2-u_1)-T_0(s_2-s_1)+P_0(v_2\overset{\nearrow 0}{}-v_1)\right]\\&=m\left[c_{v,\text{avg}}(T_2-T_1)-T_0(s_2-s_1)\right]\\&=(2.13\,\text{kg})\left[(0.684\,\text{kJ/kg}\cdot\text{K})(357.9-298.2)\text{K}-(298.2)(0.1253\,\text{kJ/kg}\cdot\text{K})\right]\\&=\mathbf{7.74\ kJ}\end{aligned}$$

since

$$s_2-s_1=c_{v,\text{avg}}\ln\frac{T_2}{T_1}+R\ln\frac{v_2}{v_1}\overset{\nearrow 0}{}=(0.684\,\text{kJ/kg}\cdot\text{K})\ln\left(\frac{357.9\,\text{K}}{298.2\,\text{K}}\right)=0.1253\,\text{kJ/kg}\cdot\text{K}$$

8-49 Carbon steel balls are to be annealed at a rate of 2500/h by heating them first and then allowing them to cool slowly in ambient air at a specified rate. The total rate of heat transfer from the balls to the ambient air and the rate of exergy destruction due to this heat transfer are to be determined.

Assumptions 1 The thermal properties of the balls are constant. 2 There are no changes in kinetic and potential energies. 3 The balls are at a uniform temperature at the end of the process.

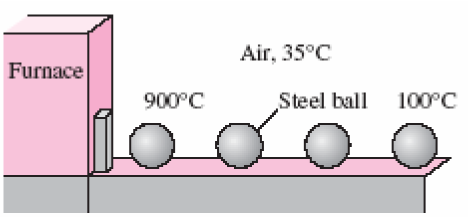
Properties The density and specific heat of the balls are given to be ρ = 7833 kg/m^3 and c_p = 0.465 kJ/kg.°C.

Analysis (*a*) We take a single ball as the system. The energy balance for this closed system can be expressed as

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

$$-Q_{\text{out}} = \Delta U_{\text{ball}} = m(u_2 - u_1)$$

$$Q_{\text{out}} = mc_p(T_1 - T_2)$$



The amount of heat transfer from a single ball is

$$m = \rho V = \rho \frac{\pi D^3}{6} = (7833\ \text{kg/m}^3)\frac{\pi (0.008\ \text{m})^3}{6} = 0.00210\ \text{kg}$$

$$Q_{\text{out}} = mc_p(T_1 - T_2) = (0.0021\ \text{kg})(0.465\ \text{kJ/kg.°C})(900-100)\text{°C} = 781\ \text{J} = 0.781\ \text{kJ (per ball)}$$

Then the total rate of heat transfer from the balls to the ambient air becomes

$$\dot{Q}_{\text{out}} = \dot{n}_{\text{ball}} Q_{\text{out}} = (1200\ \text{balls/h}) \times (0.781\ \text{kJ/ball}) = 936\ \text{kJ/h} = \mathbf{260\ \ W}$$

(*b*) The exergy destruction (or irreversibility) can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the ball and its immediate surroundings so that the boundary temperature of the extended system is at 35°C at all times:

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

$$-\frac{Q_{\text{out}}}{T_b} + S_{\text{gen}} = \Delta S_{\text{system}} \quad \rightarrow \quad S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}}$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = mc_p \ln\frac{T_2}{T_1} = (0.00210\ \text{kg})(0.465\ \text{kJ/kg.K})\ln\frac{100+273}{900+273} = -0.00112\ \text{kJ/K}$$

Substituting,

$$S_{\text{gen}} = \frac{Q_{\text{out}}}{T_b} + \Delta S_{\text{system}} = \frac{0.781\ \text{kJ}}{308\ \text{K}} - 0.00112\ \text{kJ/K} = 0.00142\ \text{kJ/K} \quad \text{(per ball)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{\text{gen}} = S_{\text{gen}} \dot{n}_{\text{ball}} = (0.00142\ \text{kJ/K} \cdot \text{ball})(1200\ \text{balls/h}) = 1.704\ \text{kJ/h.K} = 0.000473\ \ \text{kW/K}$$

Finally,

$$\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} = (308\ \text{K})(0.000473\ \text{kW/K}) = 0.146\ \text{kW} = \mathbf{146\ \ W}$$

8-61 Steam expands in a turbine from a specified state to another specified state. The actual power output of the turbine is given. The reversible power output and the second-law efficiency are to be determined.

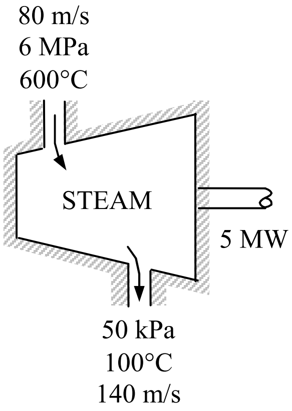
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Potential energy change is negligible. **3** The temperature of the surroundings is given to be 25°C.

Properties From the steam tables (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 6\text{ MPa} \\ T_1 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3658.8\text{ kJ/kg} \\ s_1 = 7.1693\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 50\text{ kPa} \\ T_2 = 100°\text{C} \end{array}\right\} \begin{array}{l} h_2 = 2682.4\text{ kJ/kg} \\ s_2 = 7.6953\text{ kJ/kg}\cdot\text{K} \end{array}$$

Analysis (*b*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as



$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}{}^{\nearrow 0\text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

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

$$\dot{m}(h_1 + V_1^2/2) = \dot{W}_{\text{out}} + \dot{m}(h_2 + V_2^2/2)$$

$$\dot{W}_{\text{out}} = \dot{m}\left[h_1 - h_2 + \frac{V_1^2 - V_2^2}{2}\right]$$

Substituting,

$$5000\text{ kJ/s} = \dot{m}\left(3658.8 - 2682.4 + \frac{(80\text{ m/s})^2 - (140\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right)$$

$$\dot{m} = 5.156\ \text{ kg/s}$$

The reversible (or maximum) power output is determined from the rate form of the exergy balance applied on the turbine and setting the exergy destruction term equal to zero,

$$\underbrace{\dot{X}_{\text{in}} - \dot{X}_{\text{out}}}_{\substack{\text{Rate of net exergy transfer}\\ \text{by heat, work, and mass}}} \underbrace{- \dot{X}_{\text{destroyed}}{}^{\nearrow 0\text{ (reversible)}}}_{\substack{\text{Rate of exergy}\\ \text{destruction}}} = \underbrace{\Delta \dot{X}_{\text{system}}{}^{\nearrow 0\text{ (steady)}}}_{\substack{\text{Rate of change}\\ \text{of exergy}}} = 0$$

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

$$\dot{m}\psi_1 = \dot{W}_{\text{rev,out}} + \dot{m}\psi_2$$

$$\dot{W}_{\text{rev,out}} = \dot{m}(\psi_1 - \psi_2) = \dot{m}[(h_1 - h_2) - T_0(s_1 - s_2) - \Delta\text{ke} - \Delta\text{pe}^{\nearrow 0}]$$

Substituting,

$$\begin{aligned} \dot{W}_{\text{rev,out}} &= \dot{W}_{\text{out}} - \dot{m}T_0(s_1 - s_2) \\ &= 5000\text{ kW} - (5.156\text{ kg/s})(298\text{ K})(7.1693 - 7.6953)\text{ kJ/kg}\cdot\text{K} = \mathbf{5808\ \ kW} \end{aligned}$$

(*b*) The second-law efficiency of a turbine is the ratio of the actual work output to the reversible work,

$$\eta_{\text{II}} = \frac{\dot{W}_{\text{out}}}{\dot{W}_{\text{rev,out}}} = \frac{5\text{ MW}}{5.808\text{ MW}} = \mathbf{86.1\%}$$

Discussion Note that 13.9% percent of the work potential of the steam is wasted as it flows through the turbine during this process.

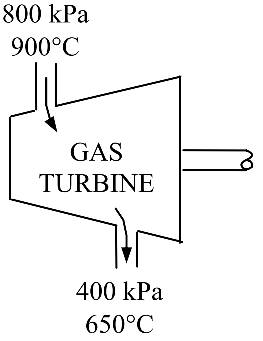
8-64 Combustion gases expand in a turbine from a specified state to another specified state. The exergy of the gases at the inlet and the reversible work output of the turbine are to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time. **2** Potential energy changes are negligible. **3** The temperature of the surroundings is given to be 25°C. **4** The combustion gases are ideal gases with constant specific heats.

Properties The constant pressure specific heat and the specific heat ratio are given to be $c_p = 1.15$ kJ/kg.K and $k = 1.3$. The gas constant R is determined from

$$R = c_p - c_v = c_p - c_p / k = c_p(1-1/k) = (1.15\,\text{kJ/kg}\cdot\text{K})(1-1/1.3) = 0.265\,\text{kJ/kg}\cdot\text{K}$$

Analysis (a) The exergy of the gases at the turbine inlet is simply the flow exergy,



$$\psi_1 = h_1 - h_0 - T_0(s_1 - s_0) + \frac{V_1^2}{2} + \cancel{gz_1}^{0}$$

where

$$\begin{aligned} s_1 - s_0 &= c_p \ln\frac{T_1}{T_0} - R\ln\frac{P_1}{P_0} \\ &= (1.15\,\text{kJ/kg}\cdot\text{K})\ln\frac{1173\,\text{K}}{298\,\text{K}} - (0.265\,\text{kJ/kg}\cdot\text{K})\ln\frac{800\,\text{kPa}}{100\,\text{kPa}} \\ &= 1.025\,\text{kJ/kg}\cdot\text{K} \end{aligned}$$

Thus,

$$\psi_1 = (1.15\,\text{kJ/kg.K})(900-25)°\text{C} - (298\,\text{K})(1.025\,\text{kJ/kg}\cdot\text{K}) + \frac{(100\,\text{m/s})^2}{2}\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = \mathbf{705.8\,kJ/kg}$$

(b) The reversible (or maximum) work output is determined from an exergy balance applied on the turbine and setting the exergy destruction term equal to zero,

$$\underbrace{\dot{X}_\text{in} - \dot{X}_\text{out}}_{\substack{\text{Rate of net exergy transfer}\\ \text{by heat, work, and mass}}} \underbrace{- \cancel{\dot{X}_\text{destroyed}}^{0\text{ (reversible)}}}_{\substack{\text{Rate of exergy}\\ \text{destruction}}} = \underbrace{\cancel{\Delta\dot{X}_\text{system}}^{0\text{ (steady)}}}_{\substack{\text{Rate of change}\\ \text{of exergy}}} = 0$$

$$\begin{aligned} \dot{X}_\text{in} &= \dot{X}_\text{out} \\ \dot{m}\psi_1 &= \dot{W}_\text{rev,out} + \dot{m}\psi_2 \\ \dot{W}_\text{rev,out} &= \dot{m}(\psi_1 - \psi_2) = \dot{m}[(h_1 - h_2) - T_0(s_1 - s_2) - \Delta\text{ke} - \cancel{\Delta\text{pe}}^{0}] \end{aligned}$$

where

$$\Delta\text{ke} = \frac{V_2^2 - V_1^2}{2} = \frac{(220\,\text{m/s})^2 - (100\,\text{m/s})^2}{2}\left(\frac{1\,\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 19.2\,\text{kJ/kg}$$

and

$$\begin{aligned} s_2 - s_1 &= c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1} \\ &= (1.15\,\text{kJ/kg}\cdot\text{K})\ln\frac{923\,\text{K}}{1173\,\text{K}} - (0.265\,\text{kJ/kg}\cdot\text{K})\ln\frac{400\,\text{kPa}}{800\,\text{kPa}} \\ &= -0.09196\,\text{kJ/kg}\cdot\text{K} \end{aligned}$$

Then the reversible work output on a unit mass basis becomes

$$\begin{aligned} w_\text{rev,out} &= h_1 - h_2 + T_0(s_2 - s_1) - \Delta\text{ke} = c_p(T_1 - T_2) + T_0(s_2 - s_1) - \Delta\text{ke} \\ &= (1.15\,\text{kJ/kg}\cdot\text{K})(900-650)°\text{C} + (298\,\text{K})(-0.09196\,\text{kJ/kg}\cdot\text{K}) - 19.2\,\text{kJ/kg} \\ &= \mathbf{240.9\,kJ/kg} \end{aligned}$$

8-79 A rigid tank initially contains saturated R-134a vapor. The tank is connected to a supply line, and R-134a is allowed to enter the tank. The mass of the R-134a that entered the tank and the exergy destroyed during this process are to be determined.

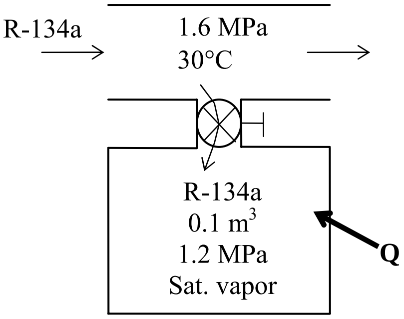
Assumptions **1** This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process since the state of fluid at the inlet remains constant. **2** Kinetic and potential energies are negligible. **3** There are no work interactions involved. **4** The direction of heat transfer is to the tank (will be verified).

Properties The properties of refrigerant are (Tables A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 1.2\text{ MPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_1 = \boldsymbol{v}_{g@1.2\text{ MPa}} = 0.01672\text{ m}^3/\text{kg} \\ u_1 = u_{g@1.2\text{ MPa}} = 253.81\text{ kJ/kg} \\ s_1 = s_{g@1.2\text{ MPa}} = 0.91303\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_2 = 1.4\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} \boldsymbol{v}_2 = \boldsymbol{v}_{f@1.4\text{ MPa}} = 0.0009166\text{ m}^3/\text{kg} \\ u_2 = u_{f@1.4\text{ MPa}} = 125.94\text{ kJ/kg} \\ s_2 = s_{f@1.4\text{ MPa}} = 0.45315\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_i = 1.6\text{ MPa} \\ T_i = 30°\text{C} \end{array}\right\} \begin{array}{l} h_i = 93.56\text{ kJ/kg} \\ s_i = 0.34554\text{ kJ/kg}\cdot\text{K} \end{array}$$



Analysis We take the tank as the system, which is a control volume. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy *h* and internal energy *u*, respectively, the mass and energy balances for this uniform-flow system can be expressed as

Mass balance:

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \quad \rightarrow \quad m_i = m_2 - m_1$$

Energy balance:

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

$$Q_{\text{in}} + m_i h_i = m_2 u_2 - m_1 u_1 \quad (\text{since } W \cong \text{ke} \cong \text{pe} \cong 0)$$

(*a*) The initial and the final masses in the tank are

$$m_1 = \frac{\boldsymbol{V}_1}{\boldsymbol{v}_1} = \frac{0.1\text{ m}^3}{0.01672\text{ m}^3/\text{kg}} = 5.983\text{ kg}$$

$$m_2 = \frac{\boldsymbol{V}_2}{\boldsymbol{v}_2} = \frac{0.1\text{ m}^3}{0.0009166\text{ m}^3/\text{kg}} = 109.10\text{ kg}$$

Then from the mass balance

$$m_i = m_2 - m_1 = 109.10 - 5.983 = \mathbf{103.11\text{ kg}}$$

The heat transfer during this process is determined from the energy balance to be

$$\begin{aligned} Q_{\text{in}} &= -m_i h_i + m_2 u_2 - m_1 u_1 \\ &= -(103.11\text{ kg})(93.56\text{ kJ/kg}) + (109.10)(125.94\text{ kJ/kg}) - (5.983\text{ kg})(253.81\text{ kJ/kg}) \\ &= 2573\text{ kJ} \end{aligned}$$

(*b*) The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. The entropy generation S_{gen} in this case is determined from an entropy balance on an *extended system* that includes the tank and its immediate surroundings so that the boundary temperature of the extended system is the surroundings temperature T_{surr} at all times. It gives

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

$$\frac{Q_{\text{in}}}{T_{\text{b,in}}} + m_i s_i + S_{\text{gen}} = \Delta S_{\text{tank}} = (m_2 s_2 - m_1 s_1)_{\text{tank}}$$ Substituting, the exergy destruction

$$S_{\text{gen}} = m_2 s_2 - m_1 s_1 - m_i s_i - \frac{Q_{\text{in}}}{T_0}$$

is determined to be

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = T_0 \left[m_2 s_2 - m_1 s_1 - m_i s_i - \frac{Q_{\text{in}}}{T_0} \right]$$
$$= (318\text{ K})\left[109.10 \times 0.45315 - 5.983 \times 0.91303 - 103.11 \times 0.34554 - (2573\text{ kJ})/(318\text{ K})\right]$$
$$= \mathbf{80.3\ kJ}$$

8-86 Liquid water is heated in a chamber by mixing it with superheated steam. For a specified mixing temperature, the mass flow rate of the steam and the rate of exergy destruction are to be determined.

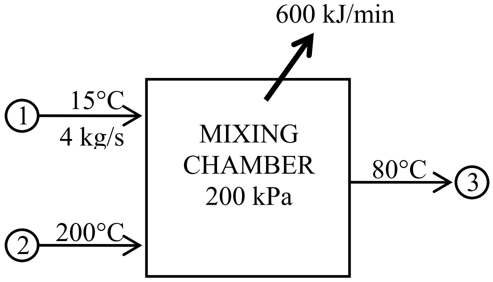
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** There are no work interactions.

Properties Noting that $T < T_{\text{sat @ 200 kPa}} = 120.23°\text{C}$, the cold water and the exit mixture streams exist as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. From Tables A-4 through A-6,

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 15°\text{C} \end{array}\right\} \begin{array}{l} h_1 \cong h_{f@15°\text{C}} = 62.98 \text{ kJ/kg} \\ s_1 \cong s_{f@15°\text{C}} = 0.22447 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ T_2 = 200°\text{C} \end{array}\right\} \begin{array}{l} h_2 = 2870.4 \text{ kJ/kg} \\ s_2 = 7.5081 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_3 = 200 \text{ kPa} \\ T_3 = 80°\text{C} \end{array}\right\} \begin{array}{l} h_3 \cong h_{f@80°\text{C}} = 335.02 \text{ kJ/kg} \\ s_3 \cong s_{f@80°\text{C}} = 1.0756 \text{ kJ/kg}\cdot\text{K} \end{array}$$



Analysis (a) We take the mixing chamber as the system, which is a control volume. The mass and energy balances for this steady-flow system can be expressed in the rate form as

Mass balance: $\dot{m}_{\text{in}} - \dot{m}_{\text{out}} = \Delta \dot{m}_{\text{system}}^{\nearrow 0 \text{ (steady)}} = 0 \longrightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy balance:

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

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

$$\dot{m}h_1 + \dot{m}_2 h_2 = \dot{Q}_{\text{out}} + \dot{m}_3 h_3$$

Combining the two relations gives $\dot{Q}_{\text{out}} = \dot{m}_1 h_1 + \dot{m}_2 h_2 - (\dot{m}_1 + \dot{m}_2) h_3 = \dot{m}_1 (h_1 - h_3) + \dot{m}_2 (h_2 - h_3)$

Solving for $\dot{m}_2$ and substituting, the mass flow rate of the superheated steam is determined to be

$$\dot{m}_2 = \frac{\dot{Q}_{\text{out}} - \dot{m}_1 (h_1 - h_3)}{h_2 - h_3} = \frac{(600/60 \text{ kJ/s}) - (4 \text{ kg/s})(62.98 - 335.02)\text{kJ/kg}}{(2870.4 - 335.02)\text{kJ/kg}} = \mathbf{0.429 \text{ kg/s}}$$

Also, $\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 4 + 0.429 = 4.429 \text{ kg/s}$

(*b*) The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ where the entropy generation S_{gen} is determined from an entropy balance on an *extended system* that includes the mixing chamber and its immediate surroundings. It gives

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

$$\dot{m}_1 s_1 + \dot{m}_2 s_2 - \dot{m}_3 s_3 - \frac{\dot{Q}_{\text{out}}}{T_{\text{b,surr}}} + \dot{S}_{\text{gen}} = 0 \rightarrow \dot{S}_{\text{gen}} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2 + \frac{\dot{Q}_{\text{out}}}{T_0}$$

Substituting, the exergy destruction is determined to be

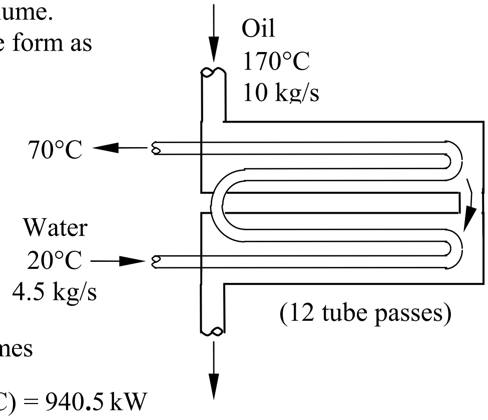
$$\begin{aligned} \dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} &= T_0 \left(\dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1 + \frac{\dot{Q}_{out}}{T_{b,surr}} \right) \\ &= (298 \text{ K})(4.429 \times 1.0756 - 0.429 \times 7.5081 - 4 \times 0.22447 + 10/298)\text{kW/K} \\ &= \mathbf{202 \text{ kW}} \end{aligned}$$

8-88 Water is heated by hot oil in a heat exchanger. The outlet temperature of the oil and the rate of exergy destruction within the heat exchanger are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. **3** Changes in the kinetic and potential energies of fluid streams are negligible. **4** Fluid properties are constant.

Properties The specific heats of water and oil are given to be 4.18 and 2.3 kJ/kg.°C, respectively.

Analysis We take the cold water tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as



$$\underbrace{\dot{E}_{in}-\dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta\dot{E}_{system}^{\nearrow 0\text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

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

$$\dot{Q}_{in} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

$$\dot{Q}_{in} = \dot{m}c_p(T_2 - T_1)$$

Then the rate of heat transfer to the cold water in this heat exchanger becomes

$$\dot{Q} = [\dot{m}c_p(T_{out} - T_{in})]_{water} = (4.5\text{ kg/s})(4.18\text{ kJ/kg.°C})(70\text{°C} - 20\text{°C}) = 940.5\text{ kW}$$

Noting that heat gain by the water is equal to the heat loss by the oil, the outlet temperature of the hot water is determined from

$$\dot{Q} = [\dot{m}c_p(T_{in} - T_{out})]_{oil} \rightarrow T_{out} = T_{in} - \frac{\dot{Q}}{\dot{m}c_p} = 170\text{°C} - \frac{940.5\text{ kW}}{(10\text{ kg/s})(2.3\text{ kJ/kg.°C})} = \mathbf{129.1°C}$$

(*b*) The rate of entropy generation within the heat exchanger is determined by applying the rate form of the entropy balance on the entire heat exchanger:

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

$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_3 s_4 + \dot{S}_{gen} = 0 \quad (\text{since } Q = 0)$$

$$\dot{m}_{water} s_1 + \dot{m}_{oil} s_3 - \dot{m}_{water} s_2 - \dot{m}_{oil} s_4 + \dot{S}_{gen} = 0$$

$$\dot{S}_{gen} = \dot{m}_{water}(s_2 - s_1) + \dot{m}_{oil}(s_4 - s_3)$$

Noting that both fluid streams are liquids (incompressible substances), the rate of entropy generation is determined to be

$$\dot{S}_{gen} = \dot{m}_{water} c_p \ln\frac{T_2}{T_1} + \dot{m}_{oil} c_p \ln\frac{T_4}{T_3}$$

$$= (4.5\text{ kg/s})(4.18\text{ kJ/kg.K})\ln\frac{70+273}{20+273} + (10\text{ kg/s})(2.3\text{ kJ/kg.K})\ln\frac{129.1+273}{170+273} = 0.736\text{ kW/K}$$

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

$$\dot{X}_{destroyed} = T_0\dot{S}_{gen} = (298\text{ K})(0.736\text{ kW/K}) = \mathbf{219\ kW}$$

8-101 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.

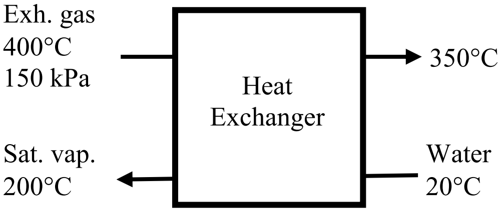
Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Air properties are used for exhaust gases. **4** Pressure drops in the heat exchanger are negligible.

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)

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

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



An energy balance on the heat exchanger gives

$$\dot{m}_a h_1 + \dot{m}_w h_3 = \dot{m}_a h_2 + \dot{m}_w h_4$$

$$\dot{m}_a c_p (T_1 - T_2) = \dot{m}_w (h_4 - h_3)$$

$$(0.8\text{ kg/s})(1.063\text{ kJ/kg°C})(400 - 350)°\text{C} = \dot{m}_w (2792.0 - 83.91)\text{kJ/kg}$$

$$\dot{m}_w = \mathbf{0.01570\ kg/s}$$

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

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

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

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

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

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

(*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,

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