8-124 An evacuated bottle is surrounded by atmospheric air. A valve is opened, and air is allowed to fill the bottle. The amount of heat transfer through the wall of the bottle when thermal and mechanical equilibrium is established and the amount of exergy destroyed 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** Air is an ideal gas. **3** Kinetic and potential energies are negligible. **4** There are no work interactions involved. **5** The direction of heat transfer is to the air in the bottle (will be verified).

Properties The gas constant of air is 0.287 kPa.m^3/kg.K (Table A-1).

Analysis We take the bottle as the system, which is a control volume since mass crosses the boundary. 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 can be expressed as

Mass balance: $m_{in} - m_{out} = \Delta m_{system} \rightarrow m_i = m_2$ (since $m_{out} = m_{initial} = 0$)

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

$$Q_{in} + m_i h_i = m_2 u_2 \text{ (since } W \cong E_{out} = E_{initial} = \text{ke} \cong \text{pe} \cong 0)$$
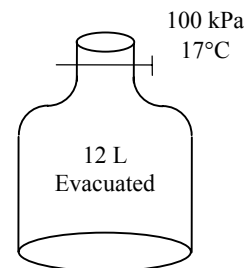
Combining the two balances:

$$Q_{in} = m_2 (u_2 - h_i)$$

where

$$m_2 = \frac{P_2 \mathcal{V}}{RT_2} = \frac{(100 \text{ kPa})(0.012 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(290 \text{ K})} = 0.0144 \text{ kg}$$

$$T_i = T_2 = 290 \text{ K} \xrightarrow{\text{Table A-17}} \begin{array}{l} h_i = 290.16 \text{ kJ/kg} \\ u_2 = 206.91 \text{ kJ/kg} \end{array}$$

Right side figure annotation: 100 kPa, 17°C, 12 L Evacuated

Substituting,

$$Q_{in} = (0.0144 \text{ kg})(206.91 - 290.16) \text{ kJ/kg} = -1.2 \text{ kJ} \rightarrow Q_{out} = \textbf{1.2 kJ}$$

Note that the negative sign for heat transfer indicates that the assumed direction is wrong. Therefore, we reversed the direction.

The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the bottle and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. The entropy balance for it can be expressed as

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

$$m_i s_i - \frac{Q_{out}}{T_{b,in}} + S_{gen} = \Delta S_{tank} = m_2 s_2 - m_1 s_1^{\nearrow 0} = m_2 s_2$$

Therefore, the total entropy generated during this process is

$$S_{gen} = -m_i s_i + m_2 s_2 + \frac{Q_{out}}{T_{b,out}} = m_2 (s_2 - s_i)^{\nearrow 0} + \frac{Q_{out}}{T_{b,out}} = \frac{Q_{out}}{T_{surr}} = \frac{1.2 \text{ kJ}}{290 \text{ K}} = 0.00415 \text{ kJ/K}$$

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

$$X_{destroyed} = T_0 S_{gen} = (290 \text{ K})(0.00415 \text{ kJ/K}) = \textbf{1.2 kJ}$$

8-125 A heat engine operates between two tanks filled with air at different temperatures. The maximum work that can be produced and the final temperatures of the tanks are to be determined.

Assumptions Air is an ideal gas with constant specific heats at room temperature.

Properties The gas constant of air is 0.287 kPa.m^3/kg.K (Table A-1). The constant volume specific heat of air at room temperature is $c_v = 0.718$ kJ/kg.K (Table A-2).

Analysis For maximum power production, the entropy generation must be zero. We take the two tanks (the heat source and heat sink) and the heat engine as the system. Noting that the system involves no heat and mass transfer and that the entropy change for cyclic devices is zero, the entropy balance can be expressed as

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}^{\nearrow 0}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$0 + S_{gen}^{\nearrow 0} = \Delta S_{tank,source} + \Delta S_{tank,sink} + \Delta S_{heat\ engine}^{\nearrow 0}$$

$$\Delta S_{tank,source} + \Delta S_{tank,sink} = 0$$

$$\left(mc_v \ln\frac{T_2}{T_1} + mR \ln\frac{V_2}{V_1}^{\curvearrowright 0} \right)_{source} + \left(mc_v \ln\frac{T_2}{T_1} + mR \ln\frac{V_2}{V_1}^{\curvearrowright 0} \right)_{sink} = 0$$

$$\ln\frac{T_2}{T_{1A}}\frac{T_2}{T_{1B}} = 0 \longrightarrow T_2^2 = T_{1A}T_{1B}$$

where T_{1A} and T_{1B} are the initial temperatures of the source and the sink, respectively, and T_2 is the common final temperature. Therefore, the final temperature of the tanks for maximum power production is

$$T_2 = \sqrt{T_{1A}T_{1B}} = \sqrt{(900\ \text{K})(300\ \text{K})} = \textbf{519.6 K}$$

The energy balance $E_{in} - E_{out} = \Delta E_{system}$ for the source and sink can be expressed as follows:

Source: $\quad -Q_{source,out} = \Delta U = mc_v(T_2 - T_{1A}) \rightarrow Q_{source,out} = mc_v(T_{1A} - T_2)$
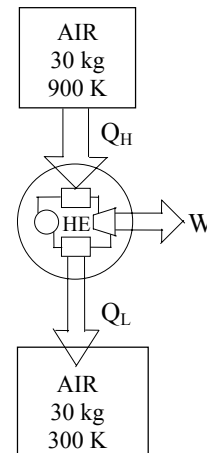
$$Q_{source,out} = mc_v(T_{1A} - T_2) = (30\ \text{kg})(0.718\ \text{kJ/kg}\cdot\text{K})(900 - 519.6)\text{K} = 8193\ \text{kJ}$$

Sink: $\quad Q_{sink,in} = mc_v(T_2 - T_{1B}) = (30\ \text{kg})(0.718\ \text{kJ/kg}\cdot\text{K})(519.6 - 300)\text{K} = 4731\ \text{kJ}$

Then the work produced in this case becomes

$$W_{max,out} = Q_H - Q_L = Q_{source,out} - Q_{sink,in} = 8193 - 4731 = \textbf{3463\ kJ}$$

Therefore, a maximum of 3463 kJ of work can be produced during this process.

8-126 A heat engine operates between two constant-pressure cylinders filled with air at different temperatures. The maximum work that can be produced and the final temperatures of the cylinders are to be determined.

Assumptions Air is an ideal gas with constant specific heats at room temperature.

Properties The gas constant of air is 0.287 kPa.m^3/kg.K (Table A-1). The constant pressure specific heat of air at room temperature is c_p = 1.005 kJ/kg.K (Table A-2).

Analysis For maximum power production, the entropy generation must be zero. We take the two cylinders (the heat source and heat sink) and the heat engine as the system. Noting that the system involves no heat and mass transfer and that the entropy change for cyclic devices is zero, the entropy balance can be expressed as

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy} \\ \text{generation}}}^{\nearrow 0} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$0 + S_{gen}^{\nearrow 0} = \Delta S_{cylinder,source} + \Delta S_{cylinder,sink} + \Delta S_{heat\ engine}^{\nearrow 0}$$

$$\Delta S_{cylinder,source} + \Delta S_{cylinder,sink} = 0$$

$$\left(mc_p \ln\frac{T_2}{T_1} - mR \ln\frac{P_2}{P_1}^{\nwarrow 0} \right)_{source} + 0 + \left(mc_p \ln\frac{T_2}{T_1} - mR \ln\frac{P_2}{P_1}^{\nwarrow 0} \right)_{sink} = 0$$

$$\ln\frac{T_2}{T_{1A}}\frac{T_2}{T_{1B}} = 0 \longrightarrow T_2^2 = T_{1A}T_{1B}$$

where T_{1A} and T_{1B} are the initial temperatures of the source and the sink, respectively, and T_2 is the common final temperature. Therefore, the final temperature of the tanks for maximum power production is

$$T_2 = \sqrt{T_{1A}T_{1B}} = \sqrt{(900\text{ K})(300\text{ K})} = \textbf{519.6 K}$$

The energy balance $E_{in} - E_{out} = \Delta E_{system}$ for the source and sink can be expressed as follows:

Source: $\quad -Q_{source,out} + W_{b,in} = \Delta U \rightarrow Q_{source,out} = \Delta H = mc_p (T_{1A} - T_2)$

$$Q_{source,out} = mc_p (T_{1A} - T_2) = (30\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(900 - 519.6)\text{K} = 11,469\text{ kJ}$$

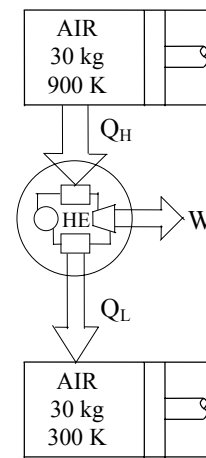*Sink:* $\quad Q_{sink,in} - W_{b,out} = \Delta U \rightarrow Q_{sink,in} = \Delta H = mc_p (T_2 - T_{1A})$

$$Q_{sink,in} = mc_p (T_2 - T_{1B}) = (30\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(519.6 - 300)\text{K} = 6621\text{ kJ}$$

Then the work produced becomes

$$W_{max,out} = Q_H - Q_L = Q_{source,out} - Q_{sink,in} = 11,469 - 6621 = \textbf{4847 kJ}$$

Therefore, a maximum of 4847 kJ of work can be produced during this process

AIR
30 kg
900 K

Q_H

HE $\rightarrow$ W

Q_L

AIR
30 kg
300 K

8-127 A pressure cooker is initially half-filled with liquid water. It is kept on the heater for 30 min. The amount water that remained in the cooker and the exergy destroyed 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 water vapor leaving the cooker remains constant. **2** Kinetic and potential energies are negligible. **3** Heat loss from the cooker is negligible.

Properties The properties of water are (Tables A-4 through A-6)

$$P_1 = 175 \text{ kPa} \rightarrow v_f = 0.001057 \text{ m}^3/\text{kg}, \ v_g = 1.0037 \text{ m}^3/\text{kg}$$

$$u_f = 486.82 \text{ kJ/kg}, \ u_g = 2524.5 \text{ kJ/kg}$$

$$s_f = 1.4850 \text{ kJ/kg.K}, \ s_g = 7.1716 \text{ kJ/kg.K}$$

$$\left. \begin{array}{l} P_e = 175 \text{ kPa} \\ \text{sat. vapor} \end{array} \right\} \begin{array}{l} h_e = h_{g @ 175 \text{ kPa}} = 2700.2 \text{ kJ/kg} \\ s_e = s_{g @ 175 \text{ kPa}} = 7.1716 \text{ kJ/kg} \cdot \text{K} \end{array}$$

Analysis (*a*) We take the cooker as the system, which is a control volume since mass crosses the boundary. 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: $m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \rightarrow m_e = m_1 - m_2$

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

$$W_{\text{e,in}} - m_e h_e = m_2 u_2 - m_1 u_1 \ \text{ (since } Q \cong \text{ke} \cong \text{pe} \cong 0)$$

The initial mass, initial internal energy, initial entropy, and final mass in the tank are

$$V_f = V_g = 2 \text{ L} = 0.002 \text{ m}^3$$

$$m_1 = m_f + m_g = \frac{V_f}{v_f} + \frac{V_g}{v_g} = \frac{0.002 \text{ m}^3}{0.001057 \text{ m}^3/\text{kg}} + \frac{0.002 \text{ m}^3}{1.0037 \text{ m}^3/\text{kg}} = 1.893 + 0.002 = 1.8945 \text{ kg}$$

$$U_1 = m_1 u_1 = m_f u_f + m_g u_g = 1.893 \times 486.82 + 0.002 \times 2524.5 = 926.6 \text{ kJ}$$

$$S_1 = m_1 s_1 = m_f s_f + m_g s_g = 1.892 \times 1.4850 + 0.002 \times 7.1716 = 2.8239 \text{ kJ/K}$$

$$m_2 = \frac{V}{v_2} = \frac{0.004 \text{ m}^3}{v_2}$$

The amount of electrical energy supplied during this process is

$$W_{e,in} = \dot{W}_{e,in} \Delta t = (0.750 \text{ kJ/s})(20 \times 60 \text{ s}) = 900 \text{ kJ}$$

Then from the mass and energy balances,

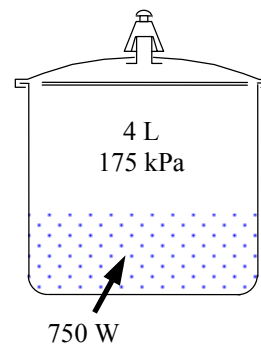$$m_e = m_1 - m_2 = 1.894 - \frac{0.004}{v_2}$$

$$900 \text{ kJ} = (1.894 - \frac{0.004}{v_2})(2700.2 \text{ kJ/kg}) + (\frac{0.004}{v_2})(u_2) - 926.6 \text{ kJ}$$

Substituting $u_2 = u_f + x_2 u_{fg}$ and $v_2 = v_f + x_2 v_{fg}$, and solving for x_2 yields

$$x_2 = 0.001918$$

Thus,

$$v_2 = v_f + x_2 v_{fg} = 0.001057 + 0.001918 \times (1.0037 - 0.001057) = 0.002654 \text{ m}^3 / \text{kg}$$

$$s_2 = s_f + x_2 s_{fg} = 1.4850 + 0.001918 \times 5.6865 = 1.5642 \text{ kJ} / \text{kg} \cdot \text{K}$$

and $\qquad m_2 = \dfrac{V}{v_2} = \dfrac{0.004 \text{ m}^3}{0.002654 \text{ m}^3 / \text{kg}} = \textbf{1.507 kg}$

(*b*) The entropy generated during this process is determined by applying the entropy balance on the cooker. Noting that there is no heat transfer and some mass leaves, the entropy balance can be expressed as

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

$$-m_e s_e + S_{\text{gen}} = \Delta S_{\text{sys}} = m_2 s_2 - m_1 s_1$$

$$S_{\text{gen}} = m_e s_e + m_2 s_2 - m_1 s_1$$

The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. Using the S_{gen} relation obtained above and substituting,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = T_0 (m_e s_e + m_2 s_2 - m_1 s_1)$$

$$= (298 \text{ K}) \big[(1.894 - 1.507) \times 7.1716 + 1.507 \times 1.5642 - 2.8239 \big]$$

$$= \textbf{689 kJ}$$

8-128 A pressure cooker is initially half-filled with liquid water. Heat is transferred to the cooker for 30 min. The amount water that remained in the cooker and the exergy destroyed 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 water vapor leaving the cooker remains constant. **2** Kinetic and potential energies are negligible. **3** Heat loss from the cooker is negligible.

Properties The properties of water are (Tables A-4 through A-6)

$$P_1 = 175kPa \rightarrow v_f = 0.001057 \text{m}^3/\text{kg}, \ v_g = 1.0037 \text{ m}^3/\text{kg}$$

$$u_f = 486.82 \text{ kJ/kg}, \ u_g = 2524.5 \text{ kJ/kg}$$

$$s_f = 1.4850 \text{ kJ/kg.K}, \ s_g = 7.1716 \text{ kJ/kg.K}$$

$$\left. \begin{array}{l} P_e = 175 \text{ kPa} \\ \text{sat.vapor} \end{array} \right\} \begin{array}{l} h_e = h_{g@175 \text{ kPa}} = 2700.2 \text{ kJ/kg} \\ s_e = s_{g@175 \text{ kPa}} = 7.1716 \text{ kJ/kg} \cdot \text{K} \end{array}$$

4 L
175 kPa

Analysis (*a*) We take the cooker as the system, which is a control volume since mass crosses the boundary. 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

750 W

Mass balance: $m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \rightarrow m_e = m_1 - m_2$

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

$$Q_{\text{in}} - m_e h_e = m_2 u_2 - m_1 u_1 \ \ (\text{since } W \cong \text{ke} \cong \text{pe} \cong 0)$$

The initial mass, initial internal energy, initial entropy, and final mass in the tank are

$$V_f = V_g = 2 \text{ L} = 0.002 \text{ m}^3$$

$$m_1 = m_f + m_g = \frac{V_f}{v_f} + \frac{V_g}{v_g} = \frac{0.002 \text{ m}^3}{0.001057 \text{ m}^3/\text{kg}} + \frac{0.002 \text{ m}^3}{1.0037 \text{ m}^3/\text{kg}} = 1.893 + 0.002 = 1.8945 \text{ kg}$$

$$U_1 = m_1 u_1 = m_f u_f + m_g u_g = 1.893 \times 486.82 + 0.002 \times 2524.5 = 926.6 \text{ kJ}$$

$$S_1 = m_1 s_1 = m_f s_f + m_g s_g = 1.892 \times 1.4850 + 0.002 \times 7.1716 = 2.8239 \text{ kJ/K}$$

$$m_2 = \frac{V}{v_2} = \frac{0.004 \text{ m}^3}{v_2}$$

The amount of heat transfer during this process is

$$Q = \dot{Q}\Delta t = (0.750 \text{ kJ/s})(20 \times 60 \text{ s}) = 900 \text{ kJ}$$
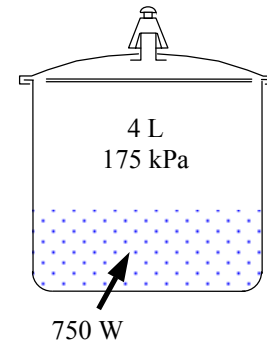
Then from the mass and energy balances,

$$m_e = m_1 - m_2 = 1.894 - \frac{0.004}{v_2}$$

$$900 \text{ kJ} = (1.894 - \frac{0.004}{v_2})(2700.2 \text{ kJ/kg}) + (\frac{0.004}{v_2})(u_2) - 926.6 \text{ kJ}$$

Substituting $u_2 = u_f + x_2 u_{fg}$ and $v_2 = v_f + x_2 v_{fg}$, and solving for x_2 yields

$$x_2 = 0.001918$$

Thus,

$$v_2 = v_f + x_2 v_{fg} = 0.001057 + 0.001918 \times (1.0037 - 0.001057) = 0.002654 \, \text{m}^3 / \text{kg}$$

$$s_2 = s_f + x_2 s_{fg} = 1.4850 + 0.001918 \times 5.6865 = 1.5642 \, \text{kJ} / \text{kg} \cdot \text{K}$$

and $\quad m_2 = \dfrac{V}{v_2} = \dfrac{0.004 \, \text{m}^3}{0.002654 \, \text{m}^3 / \text{kg}} = \mathbf{1.507 \, kg}$

(*b*) The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the cooker and its immediate surroundings so that the boundary temperature of the extended system at the location of heat transfer is the heat source temperature, T_{source} = 180°C at all times. The entropy balance for it can be expressed as

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

$$\frac{Q_{\text{in}}}{T_{\text{b,in}}} - m_e s_e + S_{\text{gen}} = \Delta S_{\text{sys}} = m_2 s_2 - m_1 s_1$$

$$S_{\text{gen}} = m_e s_e + m_2 s_2 - m_1 s_1 - \frac{Q_{\text{in}}}{T_{\text{source}}}$$

The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$. Using the S_{gen} relation obtained above and substituting,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = T_0 \left(m_e s_e + m_2 s_2 - m_1 s_1 - \frac{Q_{\text{in}}}{T_{\text{source}}} \right)$$

$$= (298 \, \text{K}) \left[(1.894 - 1.507) \times 7.1716 + 1.507 \times 1.5642 - 2.8239 - 900 / 453 \right]$$

$$= \mathbf{96.8 \, kJ}$$

Note that the exergy destroyed is much less when heat is supplied from a heat source rather than an electric resistance heater.

8-129 A heat engine operates between a nitrogen tank and an argon cylinder at different temperatures. The maximum work that can be produced and the final temperatures are to be determined.

Assumptions Nitrogen and argon are ideal gases with constant specific heats at room temperature.

Properties The constant volume specific heat of nitrogen at room temperature is $c_v = 0.743$ kJ/kg.K. The constant pressure specific heat of argon at room temperature is $c_p = 0.5203$ kJ/kg.K (Table A-2).

Analysis For maximum power production, the entropy generation must be zero. We take the tank, the cylinder (the heat source and the heat sink) and the heat engine as the system. Noting that the system involves no heat and mass transfer and that the entropy change for cyclic devices is zero, the entropy balance can be expressed as

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}^{\nearrow 0}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$0 + S_{\text{gen}}^{\nearrow 0} = \Delta S_{\text{tank,source}} + \Delta S_{\text{cylinder,sink}} + \Delta S_{\text{heat engine}}^{\nearrow 0}$$

$$(\Delta S)_{\text{source}} + (\Delta S)_{\text{sink}} = 0$$

$$\left(mc_v \ln\frac{T_2}{T_1} - mR \ln\frac{V_2}{V_1}^{\not\leftarrow 0} \right)_{\text{source}} + 0 + \left(mc_p \ln\frac{T_2}{T_1} - mR \ln\frac{P_2}{P_1}^{\not\leftarrow 0} \right)_{\text{sink}} = 0$$

Substituting,

$$(20 \text{ kg})(0.743 \text{ kJ/kg} \cdot \text{K}) \ln\frac{T_2}{1000 \text{ K}} + (10 \text{ kg})(0.5203 \text{ kJ/kg} \cdot \text{K}) \ln\frac{T_2}{300 \text{ K}} = 0$$

Solving for T_2 yields

$$T_2 = \textbf{731.8 K}$$

where T_2 is the common final temperature of the tanks for maximum power production.

The energy balance $E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$ for the source and sink can be expressed as follows:

Source: $\quad -Q_{\text{source,out}} = \Delta U = mc_v(T_2 - T_{1A}) \rightarrow Q_{\text{source,out}} = mc_v(T_{1A} - T_2)$

$$Q_{\text{source,out}} = mc_v(T_{1A} - T_2) = (20 \text{ kg})(0.743 \text{ kJ/kg} \cdot \text{K})(1000 - 731.8)\text{K} = 3985 \text{ kJ}$$
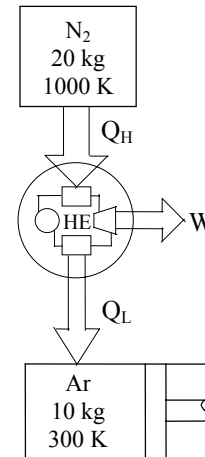
Sink: $\quad Q_{\text{sink,in}} - W_{\text{b,out}} = \Delta U \rightarrow Q_{\text{sink,in}} = \Delta H = mc_p(T_2 - T_{1A})$

$$Q_{\text{sink,in}} = mc_v(T_2 - T_{1A}) = (10 \text{ kg})(0.5203 \text{ kJ/kg} \cdot \text{K})(731.8 - 300)\text{K} = 2247 \text{ kJ}$$

Then the work produced becomes

$$W_{\text{max,out}} = Q_H - Q_L = Q_{\text{source,out}} - Q_{\text{sink,in}} = 3985 - 2247 = \textbf{1739 kJ}$$

Therefore, a maximum of 1739 kJ of work can be produced during this process

8-130 A heat engine operates between a tank and a cylinder filled with air at different temperatures. The maximum work that can be produced and the final temperatures are to be determined.

Assumptions Air is an ideal gas with constant specific heats at room temperature.

Properties The specific heats of air are $c_v = 0.718$ kJ/kg.K and $c_p = 1.005$ kJ/kg.K (Table A-2).

Analysis For maximum power production, the entropy generation must be zero. We take the tank, the cylinder (the heat source and the heat sink) and the heat engine as the system. Noting that the system involves no heat and mass transfer and that the entropy change for cyclic devices is zero, the entropy balance can be expressed as

$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}}^{\nearrow 0}\underbrace{\phantom{S_{\text{gen}}}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

$$0 + S_{\text{gen}}{}^{\nearrow 0} = \Delta S_{\text{tank,source}} + \Delta S_{\text{cylinder,sink}} + \Delta S_{\text{heat engine}}{}^{\nearrow 0}$$

$$(\Delta S)_{\text{source}} + (\Delta S)_{\text{sink}} = 0$$

$$\left(mc_v \ln\frac{T_2}{T_1} - mR \ln\frac{V_2}{V_1}^{\swarrow 0} \right)_{\text{source}} + 0 + \left(mc_p \ln\frac{T_2}{T_1} - mR \ln\frac{P_2}{P_1}^{\swarrow 0} \right)_{\text{sink}} = 0$$

$$\ln\frac{T_2}{T_{1A}} + \frac{c_p}{c_v} \ln\frac{T_2}{T_{1B}} = 0 \longrightarrow \frac{T_2}{T_{1A}}\left(\frac{T_2}{T_{1B}}\right)^k = 1 \longrightarrow T_2 = \left(T_{1A}T_{1B}^k\right)^{1/(k+1)}$$

where T_{1A} and T_{1B} are the initial temperatures of the source and the sink, respectively, and T_2 is the common final temperature. Therefore, the final temperature of the tanks for maximum power production is

$$T_2 = \left((800 \text{ K})(290 \text{ K})^{1.4}\right)^{\frac{1}{2.4}} = \textbf{442.6 K}$$

Source: $\quad -Q_{\text{source,out}} = \Delta U = mc_v(T_2 - T_{1A}) \rightarrow Q_{\text{source,out}} = mc_v(T_{1A} - T_2)$

$$Q_{\text{source,out}} = mc_v(T_{1A} - T_2) = (20 \text{ kg})(0.718 \text{ kJ/kg} \cdot \text{K})(800 - 442.6)\text{K} = 5132 \text{ kJ}$$
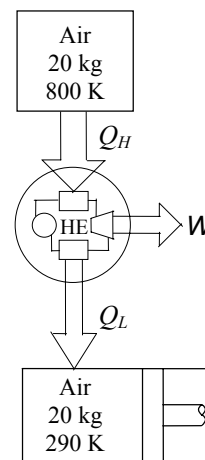
Sink: $\quad Q_{\text{sink,in}} - W_{\text{b,out}} = \Delta U \rightarrow Q_{\text{sink,in}} = \Delta H = mc_p(T_2 - T_{1A})$

$$Q_{\text{sink,in}} = mc_v(T_2 - T_{1A}) = (20 \text{ kg})(1.005 \text{ kJ/kg} \cdot \text{K})(442.6 - 290)\text{K} = 3068 \text{ kJ}$$

Then the work produced becomes

$$W_{\text{max,out}} = Q_H - Q_L = Q_{\text{source,out}} - Q_{\text{sink,in}} = 5132 - 3068 = \textbf{2064 kJ}$$

Therefore, a maximum of 2064 kJ of work can be produced during this process.

8-131 Using an incompressible substance as an example, it is to be demonstrated if closed system and flow exergies can be negative.

Analysis The availability of a closed system cannot be negative. However, the flow availability can be negative at low pressures. A closed system has zero availability at dead state, and positive availability at any other state since we can always produce work when there is a pressure or temperature differential.

To see that the flow availability can be negative, consider an incompressible substance. The flow availability can be written as

$$\psi = h - h_0 + T_0(s - s_0)$$
$$= (u - u_0) + v(P - P_0) + T_0(s - s_0)$$
$$= \xi + v(P - P_0)$$

The closed system availability ξ is always positive or zero, and the flow availability can be negative when $P \ll P_0$.

8-132 A relation for the second-law efficiency of a heat engine operating between a heat source and a heat sink at specified temperatures is to be obtained.

Analysis The second-law efficiency is defined as the ratio of the availability recovered to availability supplied during a process. The work W produced is the availability recovered. The decrease in the availability of the heat supplied Q_H is the availability supplied or invested.

Therefore,

$$\eta_{II} = \frac{W}{\left(1 - \dfrac{T_0}{T_H}\right)Q_H - \left(1 - \dfrac{T_0}{T_L}\right)(Q_H - W)}$$

Note that the first term in the denominator is the availability of heat supplied to the heat engine whereas the second term is the availability of the heat rejected by the heat engine. The difference between the two is the availability consumed during the process.
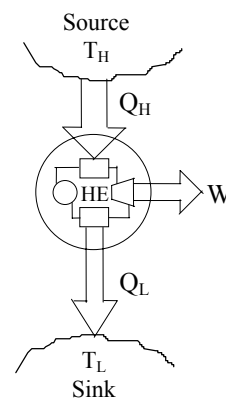
8-133E Large brass plates are heated in an oven at a rate of 300/min. The rate of heat transfer to the plates in the oven and the rate of exergy destruction associated with this heat transfer process are to be determined.

Assumptions **1** The thermal properties of the plates are constant. **2** The changes in kinetic and potential energies are negligible. **3** The environment temperature is 75°F.

Properties The density and specific heat of the brass are given to be $\rho = 532.5$ lbm/ft^3 and $c_p = 0.091$ Btu/lbm.°F.

Analysis We take the plate to be the system. The energy balance for this closed system can be expressed as

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

$$Q_{in} = \Delta U_{plate} = m(u_2 - u_1) = mc(T_2 - T_1)$$

The mass of each plate and the amount of heat transfer to each plate is

$$m = \rho V = \rho LA = (532.5 \text{ lbm/ft}^3)[(1.2/12 \text{ ft})(2 \text{ ft})(2 \text{ ft})] = 213 \text{ lbm}$$

$$Q_{in} = mc(T_2 - T_1) = (213 \text{ lbm/plate})(0.091 \text{ Btu/lbm.°F})(1000 - 75)°F = 17,930 \text{ Btu/plate}$$

Then the total rate of heat transfer to the plates becomes

$$\dot{Q}_{total} = \dot{n}_{plate} Q_{in, \, per \, plate} = (300 \text{ plates/min}) \times (17,930 \text{ Btu/plate}) = \textbf{5,379,000 Btu/min = 89,650 Btu/s}$$

We again take a single plate as the system. The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the plate and its immediate surroundings so that the boundary temperature of the extended system is at 1300°F at all times:

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

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

where

$$\Delta S_{system} = m(s_2 - s_1) = mc_{avg} \ln \frac{T_2}{T_1} = (213 \text{ lbm})(0.091 \text{ Btu/lbm.R}) \ln \frac{(1000 + 460) \text{ R}}{(75 + 460) \text{ R}} = 19.46 \text{ Btu/R}$$

Substituting,

$$S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system} = -\frac{17,930 \text{ Btu}}{1300 + 460 \text{ R}} + 19.46 \text{ Btu/R} = 9.272 \text{ Btu/R} \quad \text{(per plate)}$$

Then the rate of entropy generation becomes

$$\dot{S}_{gen} = S_{gen} \dot{n}_{ball} = (9.272 \text{ Btu/R} \cdot \text{plate})(300 \text{ plates/min}) = 2781 \text{ Btu/min.R} = 46.35 \text{ Btu/s.R}$$

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

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} = (535 \text{ R})(46.35 \text{ Btu/s.R}) = \textbf{24,797 Btu/s}$$

8-134 Long cylindrical steel rods are heat-treated in an oven. The rate of heat transfer to the rods in the oven and the rate of exergy destruction associated with this heat transfer process are to be determined.

Assumptions **1** The thermal properties of the rods are constant. **2** The changes in kinetic and potential energies are negligible. **3** The environment temperature is 30°C.

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

Analysis Noting that the rods enter the oven at a velocity of 3 m/min and exit at the same velocity, we can say that a 3-m long section of the rod is heated in the oven in 1 min. Then the mass of the rod heated in 1 minute is

$$m = \rho V = \rho LA = \rho L(\pi D^2 / 4) = (7833 \text{ kg} / \text{m}^3)(3 \text{ m})[\pi(0.1 \text{ m})^2 / 4] = 184.6 \text{ kg}$$

We take the 3-m section of the rod in the oven as the system. The energy balance
for this closed system can be expressed as

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

$$Q_{in} = \Delta U_{rod} = m(u_2 - u_1) = mc(T_2 - T_1)$$

Substituting,

$$Q_{in} = mc(T_2 - T_1) = (184.6 \text{ kg})(0.465 \text{ kJ/kg.°C})(700 - 30)°C = 57{,}512 \text{ kJ}$$

Noting that this much heat is transferred in 1 min, the rate of heat transfer to the rod becomes

$$\dot{Q}_{in} = Q_{in} / \Delta t = (57{,}512 \text{ kJ})/(1 \text{ min}) = 57{,}512 \text{ kJ/min} = \textbf{958.5 kW}$$

We again take the 3-m long section of the rod as the system The entropy generated during this process can be determined by applying an entropy balance on an *extended system* that includes the rod and its immediate surroundings so that the boundary temperature of the extended system is at 900°C at all times:

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

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

where

$$\Delta S_{system} = m(s_2 - s_1) = mc_{avg} \ln \frac{T_2}{T_1} = (184.6 \text{ kg})(0.465 \text{ kJ/kg.K}) \ln \frac{700 + 273}{30 + 273} = 100.1 \text{ kJ/K}$$

Substituting,

$$S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system} = -\frac{57{,}512 \text{ kJ}}{(900 + 273) \text{ R}} + 100.1 \text{ kJ/K} = 51.1 \text{ kJ/K}$$

Noting that this much entropy is generated in 1 min, the rate of entropy generation becomes

$$\dot{S}_{gen} = \frac{S_{gen}}{\Delta t} = \frac{51.1 \text{ kJ/K}}{1 \text{ min}} = 51.1 \text{ kJ/min.K} = 0.852 \text{ kW/K}$$

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

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} = (298 \text{ K})(0.852 \text{ kW/K}) = \textbf{254 kW}$$

8-135 Steam is condensed by cooling water in the condenser of a power plant. The rate of condensation of steam and the rate of exergy destruction 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 enthalpy and entropy of vaporization of water at 60°C are h_{fg} =2357.7 kJ/kg and s_{fg}= 7.0769 kJ/kg.K (Table A-4). The specific heat of water at room temperature is c_p = 4.18 kJ/kg.°C (Table A-3).

Analysis (*a*) 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

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

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

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

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

Then the heat transfer rate to the cooling water in the condenser becomes

$$\dot{Q} = [\dot{m}C_p(T_{out} - T_{in})]_{\text{cooling water}}$$

$$= (140 \text{ kg/s})(4.18 \text{ kJ/kg.°C})(25°C - 15°C) = 5852 \text{ kJ/s}$$

The rate of condensation of steam is determined to be

$$\dot{Q} = (\dot{m}h_{fg})_{\text{steam}} \longrightarrow \dot{m}_{\text{steam}} = \frac{\dot{Q}}{h_{fg}} = \frac{5852 \text{ kJ/s}}{2357.7 \text{ kJ/kg}} = \textbf{2.482 kg/s}$$

(*b*) The rate of entropy generation within the condenser during this process can be determined by applying the rate form of the entropy balance on the entire condenser. Noting that the condenser is well-insulated and thus heat transfer is negligible, the entropy balance for this steady-flow system can be expressed as

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

$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} = 0 \quad (\text{since } Q = 0)$$

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

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

Noting that water is an incompressible substance and steam changes from saturated vapor to saturated liquid, the rate of entropy generation is determined to be

$$\dot{S}_{gen} = \dot{m}_{\text{water}} c_p \ln\frac{T_2}{T_1} + \dot{m}_{\text{steam}}(s_f - s_g) = \dot{m}_{\text{water}} c_p \ln\frac{T_2}{T_1} - \dot{m}_{\text{steam}} s_{fg}$$

$$= (140 \text{ kg/s})(4.18 \text{ kJ/kg.K})\ln\frac{25+273}{15+273} - (2.482 \text{ kg/s})(7.0769 \text{ kJ/kg.K}) = 2.409 \text{ kW/K}$$

Then the exergy destroyed can be determined directly from its definition $X_{\text{destroyed}} = T_0 S_{gen}$ to be

$$\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{gen} = (288 \text{ K})(2.409 \text{ kW/K}) = \textbf{694 kW}$$
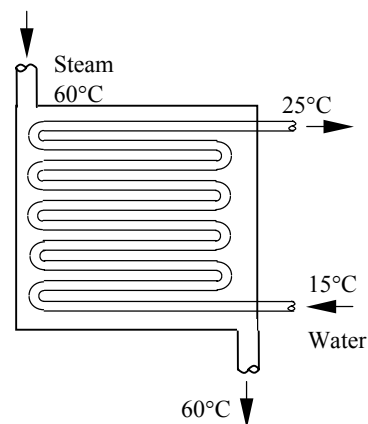
8-136 Water is heated in a heat exchanger by geothermal water. The rate of heat transfer to the water and the rate of exergy destruction within the heat exchanger are to be determined.

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. **5** The environment temperature is 25°C.

Properties The specific heats of water and geothermal fluid are given to be 4.18 and 4.31 kJ/kg.°C, respectively.
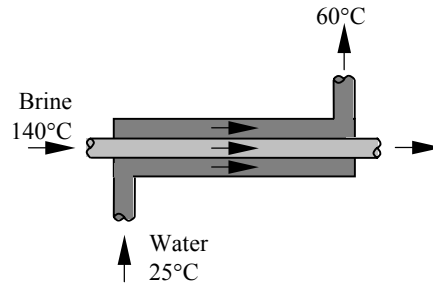
Analysis (*a*) We take the cold water tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

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

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

$$\dot{Q}_{\text{in,water}} = [\dot{m}c_p (T_{\text{out}} - T_{\text{in}})]_{\text{water}} = (0.4 \text{ kg/s})(4.18 \text{ kJ/kg.°C})(60°C - 25°C) = \mathbf{58.52 \text{ kW}}$$

Noting that heat transfer to the cold water is equal to the heat loss from the geothermal water, the outlet temperature of the geothermal water is determined from

$$\dot{Q}_{\text{out}} = [\dot{m}c_p (T_{\text{in}} - T_{\text{out}})]_{\text{geo}} \longrightarrow T_{\text{out}} = T_{\text{in}} - \frac{\dot{Q}_{\text{out}}}{\dot{m}c_p} = 140°C - \frac{58.52 \text{ kW}}{(0.3 \text{ kg/s})(4.31 \text{ kJ/kg.°C})} = \mathbf{94.7°C}$$

(*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:

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

$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{\text{gen}} = 0 \quad (\text{since } Q = 0)$$

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

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

Noting that both fresh and geothermal water are incompressible substances, the rate of entropy generation is determined to be

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

$$= (0.4 \text{ kg/s})(4.18 \text{ kJ/kg.K}) \ln \frac{60 + 273}{25 + 273} + (0.3 \text{ kg/s})(4.31 \text{ kJ/kg.K}) \ln \frac{94.7 + 273}{140 + 273} = 0.0356 \text{ kW/K}$$

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

$$\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} = (298 \text{ K})(0.0356 \text{ kW/K}) = \mathbf{10.61 \text{ kW}}$$

8-137 Ethylene glycol is cooled by water in a heat exchanger. The rate of heat transfer 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. **5** The environment temperature is 20°C.

Properties The specific heats of water and ethylene glycol are given to be 4.18 and 2.56 kJ/kg.°C, respectively.
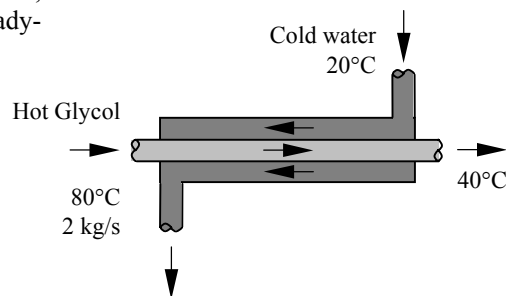
Analysis (a) We take the ethylene glycol tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

$$\dot{Q}_{out} = \dot{m}C_p(T_1 - T_2)$$

Then the rate of heat transfer becomes

$$\dot{Q}_{out} = [\dot{m}c_p(T_{in} - T_{out})]_{glycol} = (2 \text{ kg/s})(2.56 \text{ kJ/kg.°C})(80°C - 40°C) = \textbf{204.8 kW}$$

The rate of heat transfer from water must be equal to the rate of heat transfer to the glycol. Then,

$$\dot{Q}_{in} = [\dot{m}c_p(T_{out} - T_{in})]_{water} \longrightarrow \dot{m}_{water} = \frac{\dot{Q}_{in}}{c_p(T_{out} - T_{in})} = \frac{204.8 \text{ kJ/s}}{(4.18 \text{ kJ/kg.°C})(55 - 20)°C} = 1.4 \text{ kg/s}$$

(*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:

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

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

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

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

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

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

$$= (2 \text{ kg/s})(2.56 \text{ kJ/kg.K}) \ln\frac{40 + 273}{80 + 273} + (1.4 \text{ kg/s})(4.18 \text{ kJ/kg.K}) \ln\frac{55 + 273}{20 + 273} = 0.0446 \text{ kW/K}$$

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

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} = (293 \text{ K})(0.0446 \text{ kW/K}) = \textbf{13.1 kW}$$

8-138 Oil is to be cooled by water in a thin-walled heat exchanger. The rate of heat transfer 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 2.20 kJ/kg.°C, respectively.
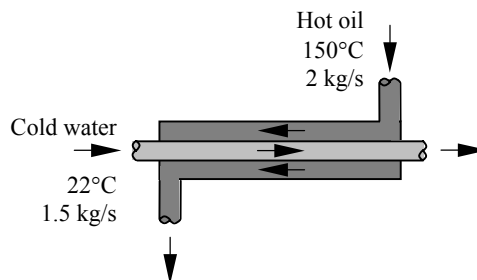
Analysis We take the oil tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

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

Hot oil
150°C
2 kg/s

Cold water
22°C
1.5 kg/s

Then the rate of heat transfer from the oil becomes

$$\dot{Q}_{\text{out}} = [\dot{m}c_p (T_{\text{in}} - T_{\text{out}})]_{\text{oil}} = (2 \text{ kg/s})(2.2 \text{ kJ/kg.°C})(150°C - 40°C) = \mathbf{484\ kW}$$

Noting that heat lost by the oil is gained by the water, the outlet temperature of water is determined from

$$\dot{Q} = [\dot{m}c_p (T_{\text{in}} - T_{\text{out}})]_{\text{water}} \longrightarrow T_{\text{out}} = T_{\text{in}} + \frac{\dot{Q}}{\dot{m}c_p} = 22°C - \frac{484 \text{ kW}}{(1.5 \text{ kg/s})(4.18 \text{ kJ/kg.°C})} = \mathbf{99.2°C}$$

(*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:

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

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

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

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

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

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

$$= (2 \text{ kg/s})(2.2 \text{ kJ/kg.K}) \ln \frac{40+273}{150+273} + (1.5 \text{ kg/s})(4.18 \text{ kJ/kg.K}) \ln \frac{99.2+273}{22+273} = 0.132 \text{ kW/K}$$

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

$$\dot{X}_{\text{destroyed}} = T_0 \dot{S}_{\text{gen}} = (295 \text{ K})(0.132 \text{ kW/K}) = \mathbf{38.9\ kW}$$

8-139 A regenerator is considered to save heat during the cooling of milk in a dairy plant. The amounts of fuel and money such a generator will save per year and the rate of exergy destruction within the regenerator are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The properties of the milk are constant. **5** The environment temperature is 18°C.

Properties The average density and specific heat of milk can be taken to be $\rho_{milk} \cong \rho_{water} = 1$ kg/L and $c_{p,milk} = 3.79$ kJ/kg.°C (Table A-3).

Analysis The mass flow rate of the milk is

$$\dot{m}_{milk} = \rho \dot{V}_{milk} = (1 \text{ kg/L})(12 \text{ L/s}) = 12 \text{ kg/s} = 43{,}200 \text{ kg/h}$$

Taking the pasteurizing section as the system, the energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

Therefore, to heat the milk from 4 to 72°C as being done currently, heat must be transferred to the milk at a rate of

$$\dot{Q}_{current} = [\dot{m}c_p (T_{pasturization} - T_{refrigeration})]_{milk} = (12 \text{ kg/s})(3.79 \text{ kJ/kg.°C})(72 - 4)°C = 3093 \text{ kJ/s}$$

The proposed regenerator has an effectiveness of $\varepsilon = 0.82$, and thus it will save 82 percent of this energy. Therefore,

$$\dot{Q}_{saved} = \varepsilon \dot{Q}_{current} = (0.82)(3093 \text{ kJ/s}) = 2536 \text{ kJ/s}$$

Noting that the boiler has an efficiency of $\eta_{boiler} = 0.82$, the energy savings above correspond to fuel savings of

$$\text{Fuel Saved} = \frac{\dot{Q}_{saved}}{\eta_{boiler}} = \frac{(2536 \text{ kJ/s})}{(0.82)} \frac{(1 \text{ therm})}{(105{,}500 \text{ kJ})} = 0.02931 \text{ therm/s}$$

Noting that 1 year = 365×24=8760 h and unit cost of natural gas is \$1.04/therm, the annual fuel and money savings will be

$$\text{Fuel Saved} = (0.02931 \text{ therms/s})(8760 \times 3600 \text{ s}) = \textbf{924,450 therms/yr}$$

$$\text{Money saved} = (\text{Fuel saved})(\text{Unit cost of fuel}) = (924{,}450 \text{ therm/yr})(\$1.04/\text{therm}) = \textbf{\$961,430/yr}$$

The rate of entropy generation during this process is determined by applying the rate form of the entropy balance on an *extended system* that includes the regenerator and the immediate surroundings so that the boundary temperature is the surroundings temperature, which we take to be the cold water temperature of 18°C.:

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

Disregarding entropy transfer associated with fuel flow, the only significant difference between the two cases is the reduction is the entropy transfer to water due to the reduction in heat transfer to water, and is determined to be

$$\dot{S}_{gen, reduction} = \dot{S}_{out, reduction} = \frac{\dot{Q}_{out, reduction}}{T_{surr}} = \frac{\dot{Q}_{saved}}{T_{surr}} = \frac{2536 \text{ kJ/s}}{18 + 273} = 8.715 \text{ kW/K}$$

$$S_{gen, reduction} = \dot{S}_{gen, reduction} \Delta t = (8.715 \text{ kJ/s.K})(8760 \times 3600 \text{ s/year}) = 2.75 \times 10^8 \text{ kJ/K (per year)}$$

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

$$X_{destroyed, reduction} = T_0 S_{gen, reduction} = (291 \text{ K})(2.75 \times 10^8 \text{ kJ/K}) = \textbf{8.00} \times \textbf{10}^{\textbf{10}} \textbf{ kJ} \quad (\text{per year})$$

8-140 Exhaust gases are expanded in a turbine, which is not well-insulated. Tha actual and reversible power outputs, the exergy destroyed, and the second-law efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Potential energy change is negligible. **3** Air is an ideal gas with constant specific heats.

Properties The gas constant of air is $R = 0.287$ kJ/kg.K and the specific heat of air at the average temperature of $(750+630)/2 = 690$ºC is $c_p = 1.134$ kJ/kg.ºC (Table A-2).

Analysis (*a*) The enthalpy and entropy changes of air across the turbine are

$$\Delta h = c_p (T_1 - T_2) = (1.134 \text{ kJ/kg.°C})(750 - 630)\text{°C} = 136.08 \text{ kJ/kg}$$

$$\Delta s = c_p \ln \frac{T_1}{T_2} - R \ln \frac{P_1}{P_2}$$

$$= (1.134 \text{ kJ/kg.K})\ln \frac{(750 + 273) \text{ K}}{(630 + 273) \text{ K}} - (0.287 \text{ kJ/kg.K}) \ln \frac{1200 \text{ kPa}}{500 \text{ kPa}}$$

$$= -0.005354 \text{ kJ/kg.K}$$

The actual and reversible power outputs from the turbine are

$$\dot{W}_a = \dot{m}\Delta h - \dot{Q}_{\text{out}} = (3.4 \text{ kg/s})(136.08 \text{ kJ/kg}) - 30 \text{ kW} = \textbf{432.7 kW}$$
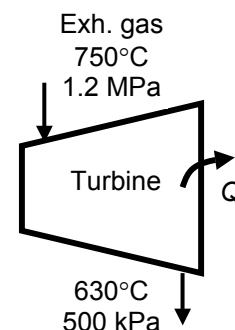
$$\dot{W}_{\text{rev}} = \dot{m}(\Delta h - T_0 \Delta s) = (3.4 \text{ kg/s})(136.08 \text{ kJ/kg}) - (25 + 273 \text{ K})(-0.005354 \text{ kJ/kg.K}) = \textbf{516.9 kW}$$

(b) The exergy destroyed in the turbine is

$$\dot{X}_{\text{dest}} = \dot{W}_{\text{rev}} - \dot{W}_a = 516.9 - 432.7 = \textbf{84.2 kW}$$

(*c*) The second-law efficiency is

$$\eta_{\text{II}} = \frac{\dot{W}_a}{\dot{W}_{\text{rev}}} = \frac{432.7 \text{ kW}}{516.9 \text{ kW}} = \textbf{0.837}$$

8-141 Refrigerant-134a is compressed in an adiabatic compressor, whose second-law efficiency is given. The actual work input, the isentropic efficiency, and the exergy destruction 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 of the compressor are (Tables A-11 through A-13)

$T_{\text{sat}@160\,\text{kPa}} = -15.60°C$

$\left. \begin{array}{l} P_1 = 160\,\text{kPa} \\ T_1 = (-15.60+3)°C \end{array} \right\} \begin{array}{l} h_1 = 243.60\,\text{kJ/kg} \\ s_1 = 0.95153\,\text{kJ/kg.K} \end{array}$

The enthalpy at the exit for if the process was isentropic is

$\left. \begin{array}{l} P_2 = 1\,\text{MPa} \\ s_2 = s_1 = 0.95153\,\text{kJ/kg.K} \end{array} \right\} h_{2s} = 282.41\,\text{kJ/kg}$

The expressions for actual and reversible works are

$w_a = h_2 - h_1 = (h_2 - 243.60)\text{kJ/kg}$

$w_{\text{rev}} = h_2 - h_1 - T_0(s_2 - s_1) = (h_2 - 243.60)\text{kJ/kg} - (25 + 273\,\text{K})(s_2 - 0.95153)\text{kJ/kg.K}$

Substituting these into the expression for the second-law efficiency

$\eta_{\text{II}} = \dfrac{w_{\text{rev}}}{w_a} \longrightarrow 0.80 = \dfrac{h_2 - 243.60 - (298)(s_2 - 0.95153)}{h_2 - 243.60}$

The exit pressure is given (1 MPa). We need one more property to fix the exit state. By a trial-error approach or using EES, we obtain the exit temperature to be 60ºC. The corresponding enthalpy and entropy values satisfying this equation are

$h_2 = 293.36\,\text{kJ/kg}$

$s_2 = 0.98492\,\text{kJ/kg.K}$

Then,
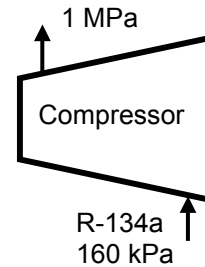
$w_a = h_2 - h_1 = 293.36 - 243.60 = \textbf{49.76kJ/kg}$

$w_{\text{rev}} = h_2 - h_1 - T_0(s_2 - s_1) = (293.36 - 243.60)\text{kJ/kg} - (25 + 273\,\text{K})(0.98492 - 0.9515)\text{kJ/kg} \cdot \text{K} = 39.81\,\text{kJ/kg}$

(b) The isentropic efficiency is determined from its definition

$\eta_s = \dfrac{h_{2s} - h_1}{h_2 - h_1} = \dfrac{(282.41 - 243.60)\text{kJ/kg}}{(293.36 - 243.60)\text{kJ/kg}} = \textbf{0.780}$

(b) The exergy destroyed in the compressor is

$x_{\text{dest}} = w_a - w_{\text{rev}} = 49.76 - 39.81 = \textbf{9.95 kJ/kg}$
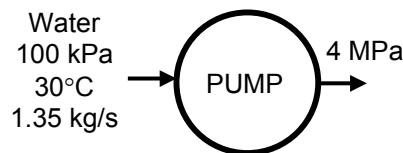
8-142 The isentropic efficiency of a water pump is specified. The actual power output, the rate of frictional heating, the exergy destruction, and the second-law efficiency are to be determined.

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

Analysis (*a*) Using saturated liquid properties at the given temperature for the inlet state (Table A-4)

$$T_1 = 30°C \atop x_1 = 0 \Bigg\} \begin{array}{l} h_1 = 125.74 \text{ kJ/kg} \\ s_1 = 0.43676 \text{ kJ/kg.K} \\ \nu_1 = 0.001004 \text{ m}^3/\text{kg} \end{array}$$

```
        Water
       100 kPa              4 MPa
        30°C   →  PUMP  →
      1.35 kg/s
```

The power input if the process was isentropic is

$$\dot{W}_s = \dot{m}\nu_1(P_2 - P_1) = (1.35 \text{ kg/s})(0.001004 \text{ m}^3/\text{kg})(4000 - 100)\text{kPa} = 5.288 \text{ kW}$$

Given the isentropic efficiency, the actual power may be determined to be

$$\dot{W}_a = \frac{\dot{W}_s}{\eta_s} = \frac{5.288 \text{ kW}}{0.70} = \textbf{7.554 kW}$$

(*b*) The difference between the actual and isentropic works is the frictional heating in the pump

$$\dot{Q}_{\text{frictional}} = \dot{W}_a - \dot{W}_s = 7.554 - 5.288 = \textbf{2.266 kW}$$

(*c*) The enthalpy at the exit of the pump for the actual process can be determined from

$$\dot{W}_a = \dot{m}(h_2 - h_1) \longrightarrow 7.555 \text{ kW} = (1.35 \text{ kg/s})(h_2 - 125.74)\text{kJ/kg} \longrightarrow h_2 = 131.33 \text{ kJ/kg}$$

The entropy at the exit is

$$P_2 = 4 \text{ MPa} \atop h_2 = 131.33 \text{ kJ/kg} \Bigg\} s_2 = 0.4420 \text{ kJ/kg.K}$$

The reversible power and the exergy destruction are

$$\begin{aligned} \dot{W}_{\text{rev}} &= \dot{m}[h_2 - h_1 - T_0(s_2 - s_1)] \\ &= (1.35 \text{ kg/s})[(131.33 - 243.60)\text{kJ/kg} - (20 + 273 \text{ K})(0.4420 - 0.95153)\text{kJ/kg.K}] = 5.487 \text{ kW} \end{aligned}$$

$$\dot{X}_{\text{dest}} = \dot{W}_a - \dot{W}_{\text{rev}} = 7.555 - 5.487 = \textbf{2.068 kW}$$

(*d*) The second-law efficiency is

$$\eta_{\text{II}} = \frac{\dot{W}_{\text{rev}}}{\dot{W}_a} = \frac{5.487 \text{ kW}}{7.555 \text{ kW}} = \textbf{0.726}$$

8-143 Argon gas is expanded adiabatically in an expansion valve. The exergy of argon 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 zero. **3** Argon is an ideal gas with constant specific heats.

Properties The properties of argon gas are $R = 0.2081$ kJ/kg.K, $c_p = 0.5203$ kJ/kg.°C (Table A-2).

Analysis (*a*) The exergy of the argon at the inlet is

$$x_1 = h_1 - h_0 - T_0(s_1 - s_0)$$

$$= c_p(T_1 - T_0) - T_0\left[c_p \ln\frac{T_1}{T_0} - R\ln\frac{P_1}{P_0}\right]$$

$$= (0.5203 \text{ kJ/kg.K})(100 - 25)°C - (298 \text{ K})\left[(0.5203 \text{ kJ/kg.K})\ln\frac{373 \text{ K}}{298 \text{ K}} - (0.2081 \text{ kJ/kg.K})\ln\frac{3500 \text{ kPa}}{100 \text{ kPa}}\right]$$

$$= \textbf{224.7 kJ/kg}$$

Argon
3.5 MPa → ⊗ 500 kPa
100°C
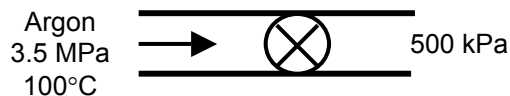
(*b*) Noting that the temperature remains constant in a throttling process, the exergy destruction is determined from

$$x_{\text{dest}} = T_0 s_{\text{gen}}$$

$$= T_0(s_2 - s_1)$$

$$= T_0\left(-R\ln\frac{P_1}{P_0}\right) = (298 \text{ K})\left[-(0.2081 \text{ kJ/kg.K})\ln\left(\frac{500 \text{ kPa}}{3500 \text{ kPa}}\right)\right]$$

$$= \textbf{120.7 kJ/kg}$$

(*c*) The second-law efficiency is

$$\eta_{\text{II}} = \frac{x_1 - x_{\text{dest}}}{x_1} = \frac{(224.7 - 120.7)\text{kJ/kg}}{224.7 \text{ kJ/kg}} = \textbf{0.463}$$

8-144 Heat is lost from the air flowing in a diffuser. The exit temperature, the rate of exergy destruction, and the second law efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Potential energy change is negligible. **3** Nitrogen is an ideal gas with variable specific heats.

Properties The gas constant of nitrogen is $R = 0.2968$ kJ/kg.K.

Analysis (*a*) For this problem, we use the properties from EES software. Remember that for an ideal gas, enthalpy is a function of temperature only whereas entropy is functions of both temperature and pressure. At the inlet of the diffuser and at the dead state, we have

$$\left. \begin{array}{l} T_1 = 15°C = 423\,K \\ P_1 = 100\,kPa \end{array} \right\} \begin{array}{l} h_1 = 130.08\,kJ/kg \\ s_1 = 7.2006\,kJ/kg \cdot K \end{array}$$

$$\left. \begin{array}{l} T_1 = 300\,K \\ P_1 = 100\,kPa \end{array} \right\} \begin{array}{l} h_0 = 1.93\,kJ/kg \\ s_0 = 6.8426\,kJ/kg \cdot K \end{array}$$
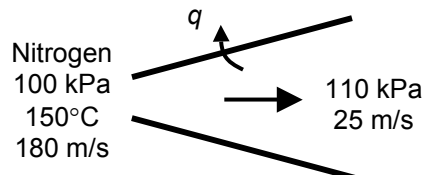
An energy balance on the diffuser gives

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

$$130.08\,kJ/kg + \frac{(180\,m/s)^2}{2}\left(\frac{1\,kJ/kg}{1000\,m^2/s^2}\right) = h_2 + \frac{(25\,m/s)^2}{2}\left(\frac{1\,kJ/kg}{1000\,m^2/s^2}\right) + 4.5\,kJ/kg$$

$$\longrightarrow h_2 = 141.47\,kJ/kg$$

The corresponding properties at the exit of the diffuser are

$$\left. \begin{array}{l} h_2 = 141.47\,kJ/kg \\ P_1 = 110\,kPa \end{array} \right\} \begin{array}{l} T_2 = \mathbf{160.9°C} = 433.9\,K \\ s_2 = 7.1989\,kJ/kg \cdot K \end{array}$$

(*b*) The mass flow rate of the nitrogen is determined to be

$$\dot{m} = \rho_2 A_2 V_2 = \frac{P_2}{RT_2} A_2 V_2 = \frac{110\,kPa}{(0.2968\,kJ/kg.K)(433.9\,K)}(0.06\,m^2)(25\,m/s) = 1.281\,kg/s$$

The exergy destruction in the nozzle is the exergy difference between the inlet and exit of the diffuser

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

$$= (1.281\,kg/s)\left[\begin{array}{l} (130.08 - 141.47)kJ/kg + \frac{(180\,m/s)^2 - (25\,m/s)^2}{2}\left(\frac{1\,kJ/kg}{1000\,m^2/s^2}\right) \\ -(300\,K)(7.2006 - 7.1989)kJ/kg.K \end{array} \right] = \mathbf{5.11\,kW}$$

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

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

$$= (1.281\,kg/s)\left[(130.08 - 1.93)\,kJ/kg + \frac{(180\,m/s)^2}{2}\left(\frac{1\,kJ/kg}{1000\,m^2/s^2}\right) - (300\,K)(7.2006 - 6.8426)kJ/kg.K \right]$$

$$= 47.35\,kW$$

$$\eta_{II} = \frac{\dot{X}_2}{\dot{X}_1} = 1 - \frac{\dot{X}_{dest}}{\dot{X}_1} = 1 - \frac{5.11\,kW}{47.35\,kW} = \mathbf{0.892}$$

Fundamentals of Engineering (FE) Exam Problems

8-145 Heat is lost through a plane wall steadily at a rate of 800 W. If the inner and outer surface temperatures of the wall are 20°C and 5°C, respectively, and the environment temperature is 0°C, the rate of exergy destruction within the wall is
(a) 40 W   (b) 17,500 W   (c) 765 W   (d) 32,800 W   (e) 0 W

Answer (a) 40 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

Q=800 "W"
T1=20 "C"
T2=5 "C"
To=0 "C"
"Entropy balance S_in - S_out + S_gen= DS_system for the wall for steady operation gives"
Q/(T1+273)-Q/(T2+273)+S_gen=0   "W/K"
X_dest=(To+273)*S_gen "W"

"Some Wrong Solutions with Common Mistakes:"
Q/T1-Q/T2+Sgen1=0; W1_Xdest=(To+273)*Sgen1   "Using C instead of K in Sgen"
Sgen2=Q/((T1+T2)/2); W2_Xdest=(To+273)*Sgen2   "Using avegage temperature in C for Sgen"
Sgen3=Q/((T1+T2)/2+273); W3_Xdest=(To+273)*Sgen3   "Using avegage temperature in K"
W4_Xdest=To*S_gen   "Using C for To"

8-146 Liquid water enters an adiabatic piping system at 15°C at a rate of 5 kg/s. It is observed that the water temperature rises by 0.5°C in the pipe due to friction. If the environment temperature is also 15°C, the rate of exergy destruction in the pipe is
(a) 8.36 kW   (b) 10.4 kW   (c) 197 kW   (d) 265 kW   (e) 2410 kW

Answer (b) 10.4 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

Cp=4.18 "kJ/kg.K"
m=5 "kg/s"
T1=15 "C"
T2=15.5 "C"
To=15 "C"
S_gen=m*Cp*ln((T2+273)/(T1+273)) "kW/K"
X_dest=(To+273)*S_gen "kW"

"Some Wrong Solutions with Common Mistakes:"
W1_Xdest=(To+273)*m*Cp*ln(T2/T1) "Using deg. C in Sgen"
W2_Xdest=To*m*Cp*ln(T2/T1) "Using deg. C in Sgen and To"
W3_Xdest=(To+273)*Cp*ln(T2/T1) "Not using mass flow rate with deg. C"
W4_Xdest=(To+273)*Cp*ln((T2+273)/(T1+273)) "Not using mass flow rate with K"

8-147 A heat engine receives heat from a source at 1500 K at a rate of 600 kJ/s and rejects the waste heat to a sink at 300 K. If the power output of the engine is 400 kW, the second-law efficiency of this heat engine is
(a) 42%   (b) 53%   (c) 83%   (d) 67%   (e) 80%

Answer (c) 83%

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

Qin=600 "kJ/s"
W=400 "kW"
TL=300 "K"
TH=1500 "K"
Eta_rev=1-TL/TH
Eta_th=W/Qin
Eta_II=Eta_th/Eta_rev

"Some Wrong Solutions with Common Mistakes:"
W1_Eta_II=Eta_th1/Eta_rev; Eta_th1=1-W/Qin "Using wrong relation for thermal efficiency"
W2_Eta_II=Eta_th "Taking second-law efficiency to be thermal efficiency"
W3_Eta_II=Eta_rev "Taking second-law efficiency to be reversible efficiency"
W4_Eta_II=Eta_th*Eta_rev "Multiplying thermal and reversible efficiencies instead of dividing"

8-148 A water reservoir contains 100 tons of water at an average elevation of 60 m. The maximum amount of electric power that can be generated from this water is
(a) 8 kWh   (b) 16 kWh   (c) 1630 kWh   (d) 16,300 kWh   (e) 58,800 kWh

Answer (b) 16 kWh

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

m=100000 "kg"
h=60 "m"
g=9.81 "m/s^2"
"Maximum power is simply the potential energy change,"
W_max=m*g*h/1000 "kJ"
W_max_kWh=W_max/3600 "kWh"

"Some Wrong Solutions with Common Mistakes:"
W1_Wmax =m*g*h/3600 "Not using the conversion factor 1000"
W2_Wmax =m*g*h/1000 "Obtaining the result in kJ instead of kWh"
W3_Wmax =m*g*h*3.6/1000 "Using worng conversion factor"
W4_Wmax =m*h/3600"Not using g and the factor 1000 in calculations"

8-149 A house is maintained at 25°C in winter by electric resistance heaters. If the outdoor temperature is 2°C, the second-law efficiency of the resistance heaters is
(a) 0%   (b) 7.7%   (c) 8.7%   (d) 13%   (e) 100%

Answer (b) 7.7%

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

TL=2+273 "K"
TH=25+273 "K"
To=TL
COP_rev=TH/(TH-TL)
COP=1
Eta_II=COP/COP_rev

"Some Wrong Solutions with Common Mistakes:"
W1_Eta_II=COP/COP_rev1; COP_rev1=TL/(TH-TL) "Using wrong relation for COP_rev"
W2_Eta_II=1-(TL-273)/(TH-273) "Taking second-law efficiency to be reversible thermal efficiency with C for temp"
W3_Eta_II=COP_rev "Taking second-law efficiency to be reversible COP"
W4_Eta_II=COP_rev2/COP; COP_rev2=(TL-273)/(TH-TL) "Using C in COP_rev relation instead of K, and reversing"

8-150 A 10-kg solid whose specific heat is 2.8 kJ/kg.°C is at a uniform temperature of -10°C. For an environment temperature of 25°C, the exergy content of this solid is
(a) Less than zero   (b) 0 kJ   (c) 22.3 kJ   (d) 62.5 kJ   (e) 980 kJ

Answer (d) 62.5 kJ

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

m=10 "kg"
Cp=2.8 "kJ/kg.K"
T1=-10+273 "K"
To=25+273 "K"
 "Exergy content of a fixed mass is x1=u1-uo-To*(s1-so)+Po*(v1-vo)"
 ex=m*(Cp*(T1-To)-To*Cp*ln(T1/To))

"Some Wrong Solutions with Common Mistakes:"
W1_ex=m*Cp*(To-T1) "Taking the energy content as the exergy content"
W2_ex=m*(Cp*(T1-To)+To*Cp*ln(T1/To)) "Using + for the second term instead of -"
W3_ex=Cp*(T1-To)-To*Cp*ln(T1/To) "Using exergy content per unit mass"
W4_ex=0 "Taking the exergy content to be zero"

8- 151 Keeping the limitations imposed by the second-law of thermodynamics in mind, choose the wrong statement below:

(a) A heat engine cannot have a thermal efficiency of 100%.
(b) For all reversible processes, the second-law efficiency is 100%.
(c) The second-law efficiency of a heat engine cannot be greater than its thermal efficiency.
(d) The second-law efficiency of a process is 100% if no entropy is generated during that process.
(e) The coefficient of performance of a refrigerator can be greater than 1.

Answer (c) The second-law efficiency of a heat engine cannot be greater than its thermal efficiency.

8-152 A furnace can supply heat steadily at a 1600 K at a rate of 800 kJ/s. The maximum amount of power that can be produced by using the heat supplied by this furnace in an environment at 300 K is
(a) 150 kW   (b) 210 kW   (c) 325 kW   (d) 650 kW   (e) 984 kW

Answer (d) 650 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

Q_in=800 "kJ/s"
TL=300 "K"
TH=1600 "K"
W_max=Q_in*(1-TL/TH) "kW"

"Some Wrong Solutions with Common Mistakes:"
W1_Wmax=W_max/2 "Taking half of Wmax"
W2_Wmax=Q_in/(1-TL/TH) "Dividing by efficiency instead of multiplying by it"
W3_Wmax =Q_in*TL/TH "Using wrong relation"
W4_Wmax=Q_in "Assuming entire heat input is converted to work"

8-153 Air is throttled from 50°C and 800 kPa to a pressure of 200 kPa at a rate of 0.5 kg/s in an environment at 25°C. The change in kinetic energy is negligible, and no heat transfer occurs during the process. The power potential wasted during this process is
(a) 0   (b) 0.20 kW   (c) 47 kW   (d) 59 kW   (e) 119 kW

Answer (d) 59 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

R=0.287 "kJ/kg.K"
Cp=1.005 "kJ/kg.K"
m=0.5 "kg/s"
T1=50+273 "K"
P1=800 "kPa"
To=25 "C"
P2=200 "kPa"
"Temperature of an ideal gas remains constant during throttling since h=const and h=h(T)"

T2=T1
ds=Cp*ln(T2/T1)-R*ln(P2/P1)
X_dest=(To+273)*m*ds "kW"

"Some Wrong Solutions with Common Mistakes:"
W1_dest=0 "Assuming no loss"
W2_dest=(To+273)*ds "Not using mass flow rate"
W3_dest=To*m*ds "Using C for To instead of K"
W4_dest=m*(P1-P2) "Using wrong relations"

8-154 Steam enters a turbine steadily at 4 MPa and 400°C and exits at 0.2 MPa and 150°C in an environment at 25°C. The decrease in the exergy of the steam as it flows through the turbine is
(a) 58 kJ/kg   (b) 445 kJ/kg   (c) 458 kJ/kg   (d) 518 kJ/kg   (e) 597 kJ/kg

Answer   (e) 597 kJ/kg

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

P1=4000 "kPa"
T1=400 "C"
P2=200 "kPa"
T2=150 "C"
To=25 "C"
h1=ENTHALPY(Steam_IAPWS,T=T1,P=P1)
s1=ENTROPY(Steam_IAPWS,T=T1,P=P1)
h2=ENTHALPY(Steam_IAPWS,T=T2,P=P2)
s2=ENTROPY(Steam_IAPWS,T=T2,P=P2)
"Exergy change of s fluid stream is Dx=h2-h1-To(s2-s1)"
-Dx=h2-h1-(To+273)*(s2-s1)

"Some Wrong Solutions with Common Mistakes:"
-W1_Dx=0 "Assuming no exergy destruction"
-W2_Dx=h2-h1 "Using enthalpy change"
-W3_Dx=h2-h1-To*(s2-s1) "Using C for To instead of K"
-W4_Dx=(h2+(T2+273)*s2)-(h1+(T1+273)*s1) "Using wrong relations for exergy"

8- 155 … 8- 158 Design and Essay Problems

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