**7–29** Refrigerant-134a enters the coils of the evaporator of a refrigeration system as a saturated liquid–vapor mixture at a pressure of 160 kPa. The refrigerant absorbs 180 kJ of heat from the cooled space, which is maintained at −5°C, and leaves as saturated vapor at the same pressure. Determine (*a*) the entropy change of the refrigerant, (*b*) the entropy change of the cooled space, and (*c*) the total entropy change for this process.

**7-29** R-134a enters an evaporator as a saturated liquid-vapor at a specified pressure. Heat is transferred to the refrigerant from the cooled space, and the liquid is vaporized. The entropy change of the refrigerant, the entropy change of the cooled space, and the total entropy change for this process are to be determined.

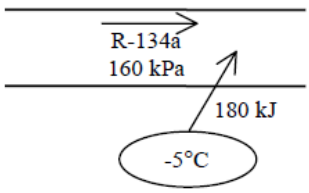
***Assumptions*** **1** Both the refrigerant and the cooled space involve no internal irreversibilities such as friction. **2** Any temperature change occurs within the wall of the tube, and thus both the refrigerant and the cooled space remain isothermal during this process. Thus it is an isothermal, internally reversible process.

***Analysis*** Noting that both the refrigerant and the cooled space undergo reversible isothermal processes, the entropy change for them can be determined from

$$\Delta S = \frac{Q}{T}$$

(*a*) The pressure of the refrigerant is maintained constant. Therefore, the temperature of the refrigerant also remains constant at the saturation value,

$$T = T_{\text{sat@160 kPa}} = -15.6°\text{C} = 257.4 \text{ K} \qquad \text{(Table A-12)}$$




Then,

$$\Delta S_{\text{refrigerant}} = \frac{Q_{\text{refrigerant,in}}}{T_{\text{refrigerant}}} = \frac{180 \text{ kJ}}{257.4 \text{ K}} = \mathbf{0.699\ kJ/K}$$

(*b*) Similarly,

$$\Delta S_{\text{space}} = -\frac{Q_{\text{space,out}}}{T_{\text{space}}} = -\frac{180 \text{ kJ}}{268 \text{ K}} = \mathbf{-0.672\ kJ/K}$$

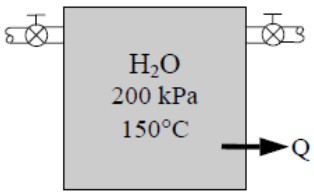
(*c*) The total entropy change of the process is

$$S_{\text{gen}} = S_{\text{total}} = \Delta S_{\text{refrigerant}} + \Delta S_{\text{space}} = 0.699 - 0.672 = \mathbf{0.027\ kJ/K}$$

**7–31** The radiator of a steam heating system has a volume of 20 L and is filled with superheated water vapor at 200 kPa and 150°C. At this moment both the inlet and the exit valves to the radiator are closed. After a while the temperature of the steam drops to 40°C as a result of heat transfer to the room air. Determine the entropy change of the steam during this process. *Answer:* −0.132 kJ/K

**7-31** The radiator of a steam heating system is initially filled with superheated steam. The valves are closed, and steam is allowed to cool until the temperature drops to a specified value by transferring heat to the room. The entropy change of the steam during this process is to be determined.

***Analysis*** From the steam tables (Tables A-4 through A-6),




$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 150°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.95986 \text{ m}^3/\text{kg} \\ s_1 = 7.2810 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_2 = 40°\text{C} \\ v_2 = v_1 \end{array}\right\} x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.95986 - 0.001008}{19.515 - 0.001008} = 0.04914$$

$$s_2 = s_f + x_2 s_{fg} = 0.5724 + (0.04914)(7.6832) = 0.9499 \text{ kJ/kg}\cdot\text{K}$$

The mass of the steam is

$$m = \frac{V}{v_1} = \frac{0.020 \text{ m}^3}{0.95986 \text{ m}^3/\text{kg}} = 0.02084 \text{ kg}$$

Then the entropy change of the steam during this process becomes

$$\Delta S = m(s_2 - s_1) = (0.02084 \text{ kg})(0.9499 - 7.2810) \text{ kJ/kg}\cdot\text{K} = \mathbf{-0.132\ kJ/K}$$

**7–32** A 0.5-m$^3$ rigid tank contains refrigerant-134a initially at 200 kPa and 40 percent quality. Heat is transferred now to the refrigerant from a source at 35°C until the pressure rises to 400 kPa. Determine (*a*) the entropy change of the refrigerant, (*b*) the entropy change of the heat source, and (*c*) the total entropy change for this process.

*Answers:* (*a*) 3.880 kJ/K, (*b*) −3.439 kJ/K, (*c*) 0.441 kJ/K

**7-32** A rigid tank is initially filled with a saturated mixture of R-134a. Heat is transferred to the tank from a source until the pressure inside rises to a specified value. The entropy change of the refrigerant, entropy change of the source, and the total entropy change for this process are to be determined. √

*Assumptions* **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions.

*Analysis* (*a*) From the refrigerant tables (Tables A-11 through A-13),

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ x_1 = 0.4 \end{array}\right\} \begin{array}{l} u_1 = u_f + x_1 u_{fg} = 38.28 + (0.4)(186.21) = 112.76 \text{ kJ/kg} \\ s_1 = s_f + x_1 s_{fg} = 0.15457 + (0.4)(0.78316) = 0.4678 \text{ kJ/kg}\cdot\text{K} \\ v_1 = v_f + x_1 v_{fg} = 0.0007533 + (0.4)(0.099867 - 0.0007533) = 0.04040 \text{ m}^3/\text{kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 400 \text{ kPa} \\ v_2 = v_1 \end{array}\right\} \begin{array}{l} x_2 = \dfrac{v_2 - v_f}{v_{fg}} = \dfrac{0.04040 - 0.0007907}{0.051201 - 0.0007907} = 0.7857 \\ u_2 = u_f + x_2 u_{fg} = 63.62 + (0.7857)(171.45) = 198.34 \text{ kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 0.24761 + (0.7857)(0.67929) = 0.7813 \text{ kJ/kg}\cdot\text{K} \end{array}$$

The mass of the refrigerant is

$$m = \frac{V}{v_1} = \frac{0.5 \text{ m}^3}{0.04040 \text{ m}^3/\text{kg}} = 12.38 \text{ kg}$$

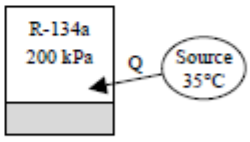
Then the entropy change of the refrigerant becomes

$$\Delta S_{\text{system}} = m(s_2 - s_1) = (12.38 \text{ kg})(0.7813 - 0.4678) \text{ kJ/kg}\cdot\text{K} = 3.880 \text{ kJ/K}$$

(*b*) We take the tank as the system. This is a closed system since no mass enters or leaves. Noting that the volume of the system is constant and thus there is no boundary work, the energy balance for this stationary closed system can be expressed as

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

$$Q_{\text{in}} = \Delta U = m(u_2 - u_1)$$




Substituting,

$$Q_{\text{in}} = m(u_2 - u_1) = (12.38 \text{ kg})(198.34 - 112.76) = 1059 \text{ kJ}$$

The heat transfer for the source is equal in magnitude but opposite in direction. Therefore,

$$Q_{\text{source, out}} = -Q_{\text{tank, in}} = -1059 \text{ kJ}$$

and

$$\Delta S_{\text{source}} = -\frac{Q_{\text{source,out}}}{T_{\text{source}}} = -\frac{1059 \text{ kJ}}{308 \text{ K}} = -3.439 \text{ kJ/K}$$

(*c*) The total entropy change for this process is

$$\Delta S_{\text{total}} = \Delta S_{\text{system}} + \Delta S_{\text{source}} = 3.880 + (-3.439) = 0.442 \text{ kJ/K}$$

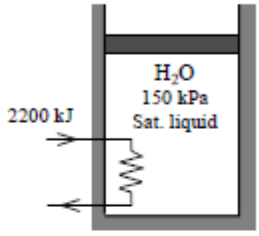
**7–38** An insulated piston–cylinder device contains 5 L of saturated liquid water at a constant pressure of 150 kPa. An electric resistance heater inside the cylinder is now turned on, and 2200 kJ of energy is transferred to the steam. Determine the entropy change of the water during this process.

*Answer:* 5.72 kJ/K

**7-38** An insulated cylinder is initially filled with saturated liquid water at a specified pressure. The water is heated electrically at constant pressure. The entropy change of the water during this process is to be determined.

*Assumptions* **1** The kinetic and potential energy changes are negligible. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

*Analysis* From the steam tables (Tables A-4 through A-6),




$$\left.\begin{array}{l} P_1 = 150 \text{ kPa} \\ sat.liquid \end{array}\right\} \begin{array}{l} v_1 = v_{f@150\text{ kPa}} = 0.001053 \text{ m}^3/\text{kg} \\ h_1 = h_{f@150\text{ kPa}} = 467.13 \text{ kJ/kg} \\ s_1 = s_{f@150\text{ kPa}} = 1.4337 \text{ kJ/kg}\cdot\text{K} \end{array}$$

Also, $$m = \frac{V}{v_1} = \frac{0.005 \text{ m}^3}{0.001053 \text{ m}^3/\text{kg}} = 4.75 \text{ kg}$$

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

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

$$W_{e,in} - W_{b,out} = \Delta U$$

$$W_{e,in} = m(h_2 - h_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. Solving for $h_2$,

$$h_2 = h_1 + \frac{W_{e,in}}{m} = 467.13 + \frac{2200 \text{ kJ}}{4.75 \text{ kg}} = 930.33 \text{ kJ/kg}$$

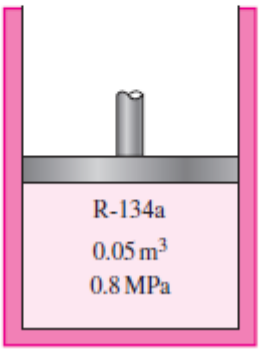
Thus,

$$\left.\begin{array}{l} P_2 = 150 \text{ kPa} \\ h_2 = 930.33 \text{ kJ/kg} \end{array}\right\} \begin{array}{l} x_2 = \dfrac{h_2 - h_f}{h_{fg}} = \dfrac{930.33 - 467.13}{2226.0} = 0.2081 \\ s_2 = s_f + x_2 s_{fg} = 1.4337 + (0.2081)(5.7894) = 2.6384 \text{ kJ/kg}\cdot\text{K} \end{array}$$

Then the entropy change of the water becomes

$$\Delta S = m(s_2 - s_1) = (4.75 \text{ kg})(2.6384 - 1.4337)\text{kJ/kg}\cdot\text{K} = \mathbf{5.72} \text{ kJ/K}$$

**7–39** An insulated piston–cylinder device contains 0.05 $m^3$ of saturated refrigerant-134a vapor at 0.8-MPa pressure. The refrigerant is now allowed to expand in a reversible manner until the pressure drops to 0.4 MPa. Determine (*a*) the final temperature in the cylinder and (*b*) the work done by the refrigerant.

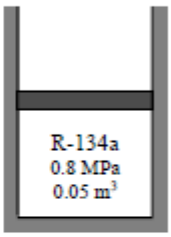



**7-39** An insulated cylinder is initially filled with saturated R-134a vapor at a specified pressure. The refrigerant expands in a reversible manner until the pressure drops to a specified value. The final temperature in the cylinder and the work done by the refrigerant are to be determined.

*Assumptions* 1 The kinetic and potential energy changes are negligible. 2 The cylinder is well-insulated and thus heat transfer is negligible. 3 The thermal energy stored in the cylinder itself is negligible. 4 The process is stated to be reversible.

*Analysis* (*a*) This is a reversible adiabatic (i.e., isentropic) process, and thus $s_2 = s_1$. From the refrigerant tables (Tables A-11 through A-13),

$$\left.\begin{array}{l} P_1 = 0.8 \text{ MPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} v_1 = v_{g@0.8\text{ MPa}} = 0.025621 \text{ m}^3/\text{kg} \\ u_1 = u_{g@0.8\text{ MPa}} = 246.79 \text{ kJ/kg} \\ s_1 = s_{g@0.8\text{ MPa}} = 0.91835 \text{ kJ/kg}\cdot\text{K} \end{array}$$




Also,

$$m = \frac{V}{v_1} = \frac{0.05 \text{ m}^3}{0.025621 \text{ m}^3/\text{kg}} = 1.952 \text{ kg}$$

and

$$\left.\begin{array}{l} P_2 = 0.4 \text{ MPa} \\ s_2 = s_1 \end{array}\right\} \begin{array}{l} x_2 = \dfrac{s_2 - s_f}{s_{fg}} = \dfrac{0.91835 - 0.24761}{0.67929} = 0.9874 \\ u_2 = u_f + x_2 u_{fg} = 63.62 + (0.9874)(171.45) = 232.91 \text{ kJ/kg} \end{array}$$

$$T_2 = T_{\text{sat@0.4 MPa}} = \mathbf{8.91°C}$$

(*b*) 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 adiabatic closed system can be expressed as

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

$$-W_{\text{b,out}} = \Delta U$$

$$W_{\text{b,out}} = m(u_1 - u_2)$$

Substituting, the work done during this isentropic process is determined to be

$$W_{\text{b,out}} = m(u_1 - u_2) = (1.952 \text{ kg})(246.79 - 232.91) \text{ kJ/kg} = \mathbf{27.09 \text{ kJ}}$$

**7–41** Refrigerant-134a enters an adiabatic compressor as saturated vapor at 160 kPa at a rate of 2 m³/min and is compressed to a pressure of 900 kPa. Determine the minimum power that must be supplied to the compressor.

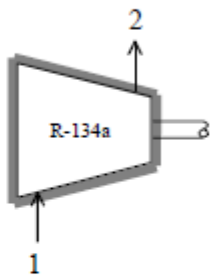
**7-41** Saturated Refrigerant-134a vapor at 160 kPa is compressed steadily by an adiabatic compressor. The minimum power input to the compressor is to be determined.

*Assumptions* **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** The device is adiabatic and thus heat transfer is negligible.

*Analysis* The power input to an adiabatic compressor will be a minimum when the compression process is reversible. For the reversible adiabatic process we have $s_2 = s_1$. From the refrigerant tables (Tables A-11 through A-13),

$$\left.\begin{array}{l} P_1 = 160 \text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} v_1 = v_{g@160\text{ kPa}} = 0.12348 \text{ m}^3/\text{kg} \\ h_1 = h_{g@160\text{ kPa}} = 241.11 \text{ kJ/kg} \\ s_1 = s_{g@160\text{ kPa}} = 0.9419 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 900 \text{ kPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 277.06 \text{ kJ/kg}$$




Also,

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{2 \text{ m}^3/\text{min}}{0.12348 \text{ m}^3/\text{kg}} = 16.20 \text{ kg/min} = 0.27 \text{ kg/s}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the compressor 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

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

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

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

$$\dot{W}_{in} = \dot{m}(h_2 - h_1)$$

Substituting, the minimum power supplied to the compressor is determined to be

$$\dot{W}_{in} = (0.27 \text{ kg/s})(277.06 - 241.11)\text{kJ/kg} = \mathbf{9.71 \text{ kW}}$$

**7–44** A heavily insulated piston–cylinder device contains 0.05 m³ of steam at 300 kPa and 150°C. Steam is now compressed in a reversible manner to a pressure of 1 MPa. Determine the work done on the steam during this process.

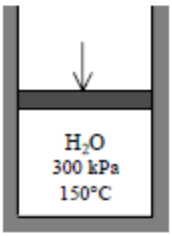
**7-44** An insulated cylinder is initially filled with superheated steam at a specified state. The steam is compressed in a reversible manner until the pressure drops to a specified value. The work input during this process is to be determined.

*Assumptions* **1** The kinetic and potential energy changes are negligible. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The process is stated to be reversible.

*Analysis* This is a reversible adiabatic (i.e., isentropic) process, and thus $s_2 = s_1$. From the steam tables (Tables A-4 through A-6),

$$\left.\begin{array}{l} P_1 = 300\text{ kPa} \\ T_1 = 150°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.63402\text{ m}^3/\text{kg} \\ u_1 = 2571.0\text{ kJ/kg} \\ s_1 = 7.0792\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1\text{ MPa} \\ s_2 = s_1 \end{array}\right\} u_2 = 2773.8\text{ kJ/kg}$$




Also,

$$m = \frac{V}{v_1} = \frac{0.05\text{ m}^3}{0.63402\text{ m}^3/\text{kg}} = 0.0789\text{ kg}$$

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 adiabatic closed system can be expressed as

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

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

Substituting, the work input during this adiabatic process is determined to be

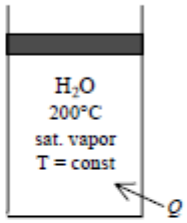
$$W_{b,in} = m(u_2 - u_1) = (0.0789\text{ kg})(2773.8 - 2571.0)\text{ kJ/kg} = \mathbf{16.0\ kJ}$$

**7–46** A piston–cylinder device contains 1.2 kg of saturated water vapor at 200°C. Heat is now transferred to steam, and steam expands reversibly and isothermally to a final pressure of 800 kPa. Determine the heat transferred and the work done during this process.

**7-46** A cylinder is initially filled with saturated water vapor at a specified temperature. Heat is transferred to the steam, and it expands in a reversible and isothermal manner until the pressure drops to a specified value. The heat transfer and the work output for this process are to be determined.

*Assumptions* **1** The kinetic and potential energy changes are negligible. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** The thermal energy stored in the cylinder itself is negligible. **4** The process is stated to be reversible and isothermal.

*Analysis* From the steam tables (Tables A-4 through A-6),




$$\left.\begin{array}{l} T_1 = 200°\text{C} \\ sat.vapor \end{array}\right\} \begin{array}{l} u_1 = u_{g@200°\text{C}} = 2594.2 \text{ kJ/kg} \\ s_1 = s_{g@200°\text{C}} = 6.4302 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 800 \text{ kPa} \\ T_2 = T_1 \end{array}\right\} \begin{array}{l} u_2 = 2631.1 \text{ kJ/kg} \\ s_2 = 6.8177 \text{ kJ/kg}\cdot\text{K} \end{array}$$

The heat transfer for this reversible isothermal process can be determined from

$$Q = T\Delta S = Tm(s_2 - s_1) = (473 \text{ K})(1.2 \text{ kg})(6.8177 - 6.4302)\text{kJ/kg}\cdot\text{K} = \mathbf{219.9 \ \ kJ}$$

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 closed system can be expressed as

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

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

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

Substituting, the work done during this process is determined to be

$$W_{b,out} = 219.9 \text{ kJ} - (1.2 \text{ kg})(2631.1 - 2594.2) \text{ kJ/kg} = \mathbf{175.6 \ \ kJ}$$

**7–48** A piston–cylinder device contains 5 kg of steam at 100°C with a quality of 50 percent. This steam undergoes two processes as follows:

1-2 Heat is transferred to the steam in a reversible manner while the temperature is held constant until the steam exists as a saturated vapor.

2-3 The steam expands in an adiabatic, reversible process until the pressure is 15 kPa.

(*a*) Sketch these processes with respect to the saturation lines on a single *T-s* diagram.

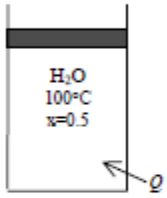
(*b*) Determine the heat added to the steam in process 1-2, in kJ.

(*c*) Determine the work done by the steam in process 2-3, in kJ.

**7-48** A cylinder is initially filled with saturated water vapor mixture at a specified temperature. Steam undergoes a reversible heat addition and an isentropic process. The processes are to be sketched and heat transfer for the first process and work done during the second process are to be determined.

***Assumptions*** **1** The kinetic and potential energy changes are negligible. **2** The thermal energy stored in the cylinder itself is negligible. **3** Both processes are reversible.

***Analysis*** (b) From the steam tables (Tables A-4 through A-6),




$$\left.\begin{array}{l} T_1 = 100°\text{C} \\ x = 0.5 \end{array}\right\} h_1 = h_f + xh_{fg} = 419.17 + (0.5)(2256.4) = 1547.4 \text{ kJ/kg}$$

$$\left.\begin{array}{l} T_2 = 100°\text{C} \\ x_2 = 1 \end{array}\right\} \begin{array}{l} h_2 = h_g = 2675.6 \text{ kJ/kg} \\ u_2 = u_g = 2506.0 \text{ kJ/kg} \\ s_2 = 7.3542 \text{ kJ/kg·K} \end{array}$$

$$\left.\begin{array}{l} P_3 = 15 \text{ kPa} \\ s_3 = s_2 \end{array}\right\} u_3 = 2247.9 \text{ kJ/kg}$$

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 closed system can be expressed as

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

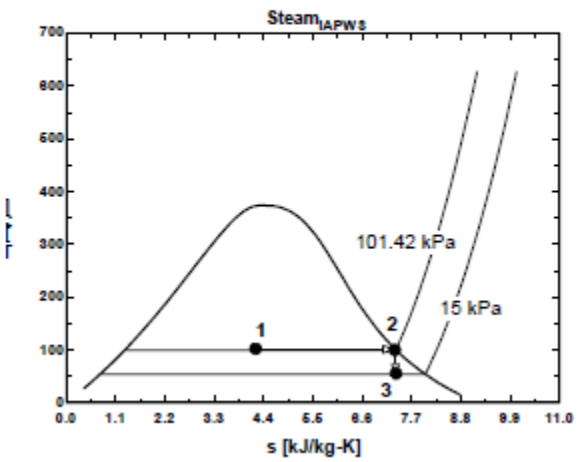
$$Q_{in} - W_{b,out} = \Delta U = m(u_2 - u_1)$$

For process 1-2, it reduces to

$$Q_{12,in} = m(h_2 - h_1) = (5 \text{ kg})(2675.6 - 1547.4)\text{kJ/kg} = \mathbf{5641 \text{ kJ}}$$

(c) For process 2-3, it reduces to

$$W_{23,b,out} = m(u_2 - u_3) = (5 \text{ kg})(2506.0 - 2247.9)\text{kJ/kg} = \mathbf{1291 \text{ kJ}}$$



**7–49** A rigid tank contains 5 kg of saturated vapor steam at 100°C. The steam is cooled to the ambient temperature of 25°C.

(*a*) Sketch the process with respect to the saturation lines on a *T*-*v* diagram.

(*b*) Determine the entropy change of the steam, in kJ/K.

(*c*) For the steam and its surroundings, determine the total entropy change or $S_{gen}$ associated with this process, in kJ/K.

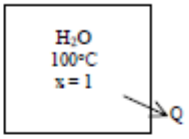
**7-49** A rigid tank contains saturated water vapor at a specified temperature. Steam is cooled to ambient temperature. The process is to be sketched and entropy changes for the steam and for the process are to be determined.

***Assumptions*** **1** The kinetic and potential energy changes are negligible.

***Analysis*** (b) From the steam tables (Tables A-4 through A-6),

$$\left.\begin{array}{l} T_1 = 100°C \\ x = 1 \end{array}\right\} \begin{array}{l} v_1 = v_g = 1.6720 \text{ kJ/kg} \\ u_1 = u_g = 2506.0 \text{ kJ/kg} \\ s_1 = 7.3542 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_2 = 25°C \\ v_2 = v_1 \end{array}\right\} \begin{array}{l} x_2 = 0.0386 \\ u_2 = 193.78 \text{ kJ/kg} \\ s_2 = 1.0715 \text{ kJ/kg}\cdot\text{K} \end{array}$$




The entropy change of steam is determined from

$$\Delta S_w = m(s_2 - s_1) = (5\text{ kg})(1.0715 - 7.3542)\text{kJ/kg}\cdot\text{K} = \mathbf{-31.41\ kJ/K}$$

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

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

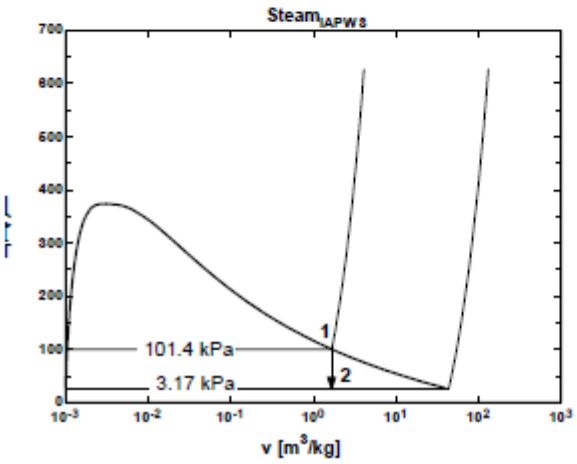
$$-Q_{out} = \Delta U = m(u_2 - u_1)$$

That is,

$$Q_{out} = m(u_1 - u_2) = (5\text{ kg})(2506.0 - 193.78)\text{kJ/kg} = 11{,}511\text{ kJ}$$

The total entropy change for the process is

$$S_{gen} = \Delta S_w + \frac{Q_{out}}{T_{surr}} = -31.41\text{ kJ/K} + \frac{11{,}511\text{ kJ}}{298\text{ K}} = \mathbf{7.39\ kJ/K}$$



**7–50** Steam at 6000 kPa and 500°C enters a steady-flow turbine. The steam expands in the turbine while doing work until the pressure is 1000 kPa. When the pressure is 1000 kPa, 10 percent of the steam is removed from the turbine for other uses. The remaining 90 percent of the steam continues to expand through the turbine while doing work and leaves the turbine at 10 kPa. The entire expansion process by the steam through the turbine is reversible and adiabatic.

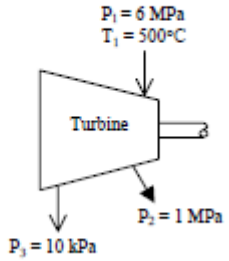
(*a*) Sketch the process on a *T-s* diagram with respect to the saturation lines. Be sure to label the data states and the lines of constant pressure.

(*b*) If the turbine has an isentropic efficiency of 85 percent, what is the work done by the steam as it flows through the turbine per unit mass of steam flowing into the turbine, in kJ/kg?

**7-50** Steam expands in an adiabatic turbine. Steam leaves the turbine at two different pressures. The process is to be sketched on a *T-s* diagram and the work done by the steam per unit mass of the steam at the inlet are to be determined.

***Assumptions*** **1** The kinetic and potential energy changes are negligible.

***Analysis*** (b) From the steam tables (Tables A-4 through A-6),



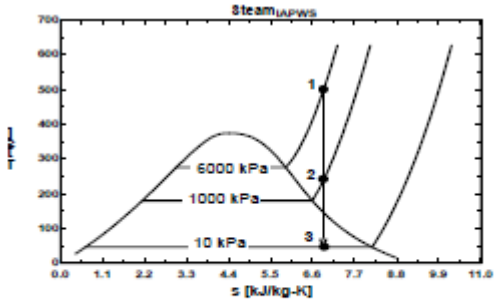

$$\left.\begin{array}{l} T_1 = 500°\text{C} \\ P_1 = 6\ \text{MPa} \end{array}\right\} \begin{array}{l} h_1 = 3423.1\ \text{kJ/kg} \\ s_1 = 6.8826\ \text{kJ/kg}\cdot\text{K} \end{array} \qquad \left.\begin{array}{l} P_2 = 1\ \text{MPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 2921.3\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 10\ \text{kPa} \\ s_3 = s_1 \end{array}\right\} \begin{array}{l} h_{3s} = 2179.6\ \text{kJ/kg} \\ x_{3s} = 0.831 \end{array}$$

A mass balance on the control volume gives

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \quad \text{where} \quad \begin{array}{l} \dot{m}_2 = 0.1\dot{m}_1 \\ \dot{m}_3 = 0.9\dot{m}_1 \end{array}$$

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




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

$$\dot{m}_1 h_1 = \dot{W}_{s,out} + \dot{m}_2 h_2 + \dot{m}_3 h_3$$

$$\dot{m}_1 h_1 = \dot{W}_{s,out} + 0.1\dot{m}_1 h_2 + 0.9\dot{m}_1 h_3$$

or

$$h_1 = w_{s,out} + 0.1h_2 + 0.9h_3$$

$$w_{s,out} = h_1 - 0.1h_2 - 0.9h_3$$

$$= 3423.1 - (0.1)(2921.3) - (0.9)(2179.6) = 1169.3\ \text{kJ/kg}$$

The actual work output per unit mass of steam at the inlet is

$$w_{out} = \eta_T w_{s,out} = (0.85)(1169.3\ \text{kJ/kg}) = \mathbf{993.9\ kJ/kg}$$

**7–53** A 50-kg copper block initially at 80°C is dropped into an insulated tank that contains 120 L of water at 25°C. Determine the final equilibrium temperature and the total entropy change for this process.

**7-53** A hot copper block is dropped into water in an insulated tank. The final equilibrium temperature of the tank and the total entropy change are to be determined.

***Assumptions*** **1** Both the water and the copper block are incompressible substances with constant specific heats at room temperature. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The tank is well-insulated and thus there is no heat transfer.

***Properties*** The density and specific heat of water at 25°C are $\rho$ = 997 kg/m$^3$ and $c_p$ = 4.18 kJ/kg.°C. The specific heat of copper at 27°C is $c_p$ = 0.386 kJ/kg.°C (Table A-3).

***Analysis*** We take the entire contents of the tank, water + copper block, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as

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

$$0 = \Delta U$$

or,

$$\Delta U_{Cu} + \Delta U_{water} = 0$$

$$[mc(T_2 - T_1)]_{Cu} + [mc(T_2 - T_1)]_{water} = 0$$

where

$$m_{water} = \rho V = (997 \text{ kg/m}^3)(0.120 \text{ m}^3) = 119.6 \text{ kg}$$

Using specific heat values for copper and liquid water at room temperature and substituting,

$$(50 \text{ kg})(0.386 \text{ kJ/kg}\cdot°\text{C})(T_2 - 80)°\text{C} + (119.6 \text{ kg})(4.18 \text{ kJ/kg}\cdot°\text{C})(T_2 - 25)°\text{C} = 0$$

$$\mathbf{T_2 = 27.0°C}$$

The entropy generated during this process is determined from

$$\Delta S_{copper} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (50 \text{ kg})(0.386 \text{ kJ/kg}\cdot\text{K}) \ln\left(\frac{300.0 \text{ K}}{353 \text{ K}}\right) = -3.140 \text{ kJ/K}$$

$$\Delta S_{water} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (119.6 \text{ kg})(4.18 \text{ kJ/kg}\cdot\text{K}) \ln\left(\frac{300.0 \text{ K}}{298 \text{ K}}\right) = 3.344 \text{ kJ/K}$$

Thus,

$$\Delta S_{total} = \Delta S_{copper} + \Delta S_{water} = -3.140 + 3.344 = \mathbf{0.204 \text{ kJ/K}}$$

**7–54** A 25-kg iron block initially at 350°C is quenched in an insulated tank that contains 100 kg of water at 18°C. Assuming the water that vaporizes during the process condenses back in the tank, determine the total entropy change during this process.

**7-54** A hot iron block is dropped into water in an insulated tank. The total entropy change during this process is to be determined.

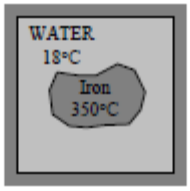
***Assumptions*** **1** Both the water and the iron block are incompressible substances with constant specific heats at room temperature. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The tank is well-insulated and thus there is no heat transfer. **4** The water that evaporates, condenses back.

***Properties*** The specific heat of water at 25°C is $c_p$ = 4.18 kJ/kg.°C. The specific heat of iron at room temperature is $c_p$ = 0.45 kJ/kg.°C (Table A-3).

***Analysis*** We take the entire contents of the tank, water + iron block, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as

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

$$0 = \Delta U$$




or,

$$\Delta U_{iron} + \Delta U_{water} = 0$$

$$[mc(T_2 - T_1)]_{iron} + [mc(T_2 - T_1)]_{water} = 0$$

Substituting,

$$(25\text{ kg})(0.45\text{ kJ/kg}\cdot\text{K})(T_2 - 350°\text{C}) + (100\text{ kg})(4.18\text{ kJ/kg}\cdot\text{K})(T_2 - 18°\text{C}) = 0$$

$$\mathbf{T_2 = 26.7°C}$$

The entropy generated during this process is determined from

$$\Delta S_{iron} = mc_{avg}\ln\left(\frac{T_2}{T_1}\right) = (25\text{ kg})(0.45\text{ kJ/kg}\cdot\text{K})\ln\left(\frac{299.7\text{ K}}{623\text{ K}}\right) = -8.232\text{ kJ/K}$$

$$\Delta S_{water} = mc_{avg}\ln\left(\frac{T_2}{T_1}\right) = (100\text{ kg})(4.18\text{ kJ/kg}\cdot\text{K})\ln\left(\frac{299.7\text{ K}}{291\text{ K}}\right) = 12.314\text{ kJ/K}$$

Thus,

$$S_{gen} = \Delta S_{total} = \Delta S_{iron} + \Delta S_{water} = -8.232 + 12.314 = \mathbf{4.08\ kJ/K}$$

***Discussion*** The results can be improved somewhat by using specific heats at average temperature.

**7–55** A 20-kg aluminum block initially at 200°C is brought into contact with a 20-kg block of iron at 100°C in an insulated enclosure. Determine the final equilibrium temperature and the total entropy change for this process. *Answers:* 168.4°C, 0.169 kJ/K

**7-55** An aluminum block is brought into contact with an iron block in an insulated enclosure. The final equilibrium temperature and the total entropy change for this process are to be determined.

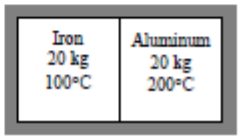
***Assumptions*** **1** Both the aluminum and the iron block are incompressible substances with constant specific heats. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The system is well-insulated and thus there is no heat transfer.

***Properties*** The specific heat of aluminum at the anticipated average temperature of 450 K is $c_p = 0.973$ kJ/kg.°C. The specific heat of iron at room temperature (the only value available in the tables) is $c_p = 0.45$ kJ/kg.°C (Table A-3).

***Analysis*** We take the iron+aluminum blocks as the system, which is a closed system. The energy balance for this system can be expressed as

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

$$0 = \Delta U$$




or,

$$\Delta U_{alum} + \Delta U_{iron} = 0$$

$$[mc(T_2 - T_1)]_{alum} + [mc(T_2 - T_1)]_{iron} = 0$$

Substituting,

$$(20\text{ kg})(0.45\text{ kJ/kg}\cdot\text{K})(T_2 - 100°\text{C}) + (20\text{ kg})(0.973\text{ kJ/kg}\cdot\text{K})(T_2 - 200°\text{C}) = 0$$

$$T_2 = \mathbf{168.4°C} = 441.4\text{ K}$$

The total entropy change for this process is determined from

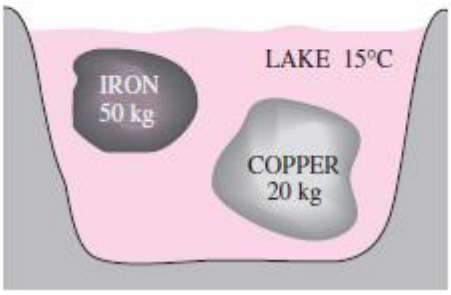
$$\Delta S_{iron} = mc_{avg}\ln\left(\frac{T_2}{T_1}\right) = (20\text{ kg})(0.45\text{ kJ/kg}\cdot\text{K})\ln\left(\frac{441.4\text{ K}}{373\text{ K}}\right) = 1.515\text{ kJ/K}$$

$$\Delta S_{alum} = mc_{avg}\ln\left(\frac{T_2}{T_1}\right) = (20\text{ kg})(0.973\text{ kJ/kg}\cdot\text{K})\ln\left(\frac{441.4\text{ K}}{473\text{ K}}\right) = -1.346\text{ kJ/K}$$

Thus,

$$\Delta S_{total} = \Delta S_{iron} + \Delta S_{alum} = 1.515 - 1.346 = \mathbf{0.169\text{ kJ/K}}$$

**7–57** A 50-kg iron block and a 20-kg copper block, both initially at 80°C, are dropped into a large lake at 15°C. Thermal equilibrium is established after a while as a result of heat transfer between the blocks and the lake water. Determine the total entropy change for this process.




**7-57** An iron block and a copper block are dropped into a large lake. The total amount of entropy change when both blocks cool to the lake temperature is to be determined.

***Assumptions*** **1** Both the water and the iron block are incompressible substances with constant specific heats at room temperature. **2** Kinetic and potential energies are negligible.

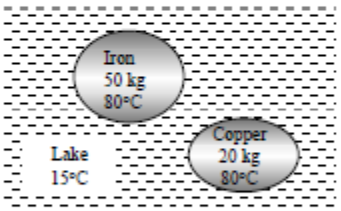
***Properties*** The specific heats of iron and copper at room temperature are $c_{iron}$ = 0.45 kJ/kg.°C and $c_{copper}$ = 0.386 kJ/kg.°C (Table A-3).

***Analysis*** The thermal-energy capacity of the lake is very large, and thus the temperatures of both the iron and the copper blocks will drop to the lake temperature (15°C) when the thermal equilibrium is established. Then the entropy changes of the blocks become

$$\Delta S_{iron} = mc_{avg}\ln\left(\frac{T_2}{T_1}\right) = (50\text{ kg})(0.45\text{ kJ/kg}\cdot\text{K})\ln\left(\frac{288\text{ K}}{353\text{ K}}\right) = -4.579\text{ kJ/K}$$

$$\Delta S_{copper} = mc_{avg}\ln\left(\frac{T_2}{T_1}\right) = (20\text{ kg})(0.386\text{ kJ/kg}\cdot\text{K})\ln\left(\frac{288\text{ K}}{353\text{ K}}\right) = -1.571\text{ kJ/K}$$

We take both the iron and the copper blocks, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as




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

$$-Q_{out} = \Delta U = \Delta U_{iron} + \Delta U_{copper}$$

or,

$$Q_{out} = [mc(T_1 - T_2)]_{iron} + [mc(T_1 - T_2)]_{copper}$$

Substituting,

$$Q_{out} = (50\text{ kg})(0.45\text{ kJ/kg}\cdot\text{K})(353 - 288)\text{K} + (20\text{ kg})(0.386\text{ kJ/kg}\cdot\text{K})(353 - 288)\text{K}$$
$$= 1964\text{ kJ}$$

Thus,

$$\Delta S_{lake} = \frac{Q_{lake,in}}{T_{lake}} = \frac{1964\text{ kJ}}{288\text{ K}} = 6.820\text{ kJ/K}$$

Then the total entropy change for this process is

$$\Delta S_{total} = \Delta S_{iron} + \Delta S_{copper} + \Delta S_{lake} = -4.579 - 1.571 + 6.820 = \mathbf{0.670\text{ kJ/K}}$$

**7–58** An adiabatic pump is to be used to compress saturated liquid water at 10 kPa to a pressure to 15 MPa in a reversible manner. Determine the work input using (*a*) entropy data from the compressed liquid table, (*b*) inlet specific volume and pressure values, (*c*) average specific volume and pressure values. Also, determine the errors involved in parts (*b*) and (*c*).

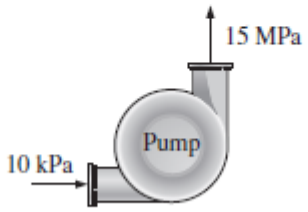



**FIGURE P7–58**

**7–66** Oxygen gas is compressed in a piston–cylinder device from an initial state of 0.8 m³/kg and 25°C to a final state of 0.1 m³/kg and 287°C. Determine the entropy change of the oxygen during this process. Assume constant specific heats.

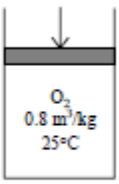
**7-66** Oxygen gas is compressed from a specified initial state to a specified final state. The entropy change of oxygen during this process is to be determined for the case of constant specific heats.

***Assumptions*** At specified conditions, oxygen can be treated as an ideal gas.

***Properties*** The gas constant and molar mass of oxygen are $R = 0.2598$ kJ/kg.K and $M = 32$ kg/kmol (Table A-1).

***Analysis*** The constant volume specific heat of oxygen at the average temperature is (Table A-2)

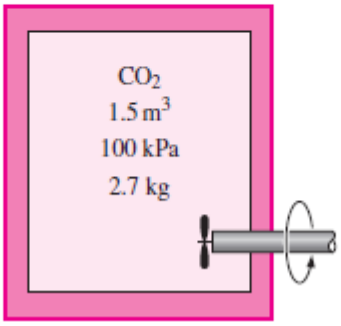
$$T_{avg} = \frac{298 + 560}{2} = 429 \text{ K} \longrightarrow c_{v,avg} = 0.690 \text{ kJ/kg} \cdot \text{K}$$




Thus,

$$\begin{aligned} s_2 - s_1 &= c_{v,avg} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} \\ &= (0.690 \text{ kJ/kg} \cdot \text{K}) \ln \frac{560 \text{ K}}{298 \text{ K}} + (0.2598 \text{ kJ/kg} \cdot \text{K}) \ln \frac{0.1 \text{ m}^3/\text{kg}}{0.8 \text{ m}^3/\text{kg}} \\ &= \mathbf{-0.105 \text{ kJ/kg} \cdot \text{K}} \end{aligned}$$

**7–67** A 1.5-m$^3$ insulated rigid tank contains 2.7 kg of carbon dioxide at 100 kPa. Now paddle-wheel work is done on the system until the pressure in the tank rises to 150 kPa. Determine the entropy change of carbon dioxide during this process. Assume constant specific heats. *Answer:* 0.719 kJ/K

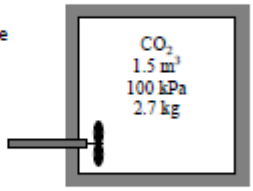



**7-67** An insulated tank contains $CO_2$ gas at a specified pressure and volume. A paddle-wheel in the tank stirs the gas, and the pressure and temperature of $CO_2$ rises. The entropy change of $CO_2$ during this process is to be determined using constant specific heats.

***Assumptions*** At specified conditions, $CO_2$ can be treated as an ideal gas with constant specific heats at room temperature.

***Properties*** The specific heat of $CO_2$ is $c_v = 0.657$ kJ/kg·K (Table A-2).

***Analysis*** Using the ideal gas relation, the entropy change is determined to be




$$\frac{P_2V}{T_2} = \frac{P_1V}{T_1} \longrightarrow \frac{T_2}{T_1} = \frac{P_2}{P_1} = \frac{150\text{ kPa}}{100\text{ kPa}} = 1.5$$

Thus,

$$\Delta S = m(s_2 - s_1) = m\left(c_{v,\text{avg}}\ln\frac{T_2}{T_1} + R\ln\frac{V_2}{V_1}^{\nearrow 0}\right) = mc_{v,\text{avg}}\ln\frac{T_2}{T_1}$$

$$= (2.7\text{ kg})(0.657\text{ kJ/kg}\cdot\text{K})\ln(1.5)$$

$$= \mathbf{0.719\ kJ/K}$$

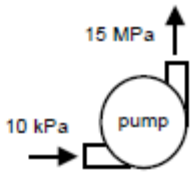
**7-58** An adiabatic pump is used to compress saturated liquid water in a reversible manner. The work input is to be determined by different approaches.

***Assumptions*** **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer to or from the fluid is negligible.

***Analysis*** The properties of water at the inlet and exit of the pump are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 10\text{ kPa} \\ x_1 = 0 \end{array}\right\} \begin{array}{l} h_1 = 191.81\text{ kJ/kg} \\ s_1 = 0.6492\text{ kJ/kg} \\ v_1 = 0.001010\text{ m}^3\text{/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 15\text{ MPa} \\ s_2 = s_1 \end{array}\right\} \begin{array}{l} h_2 = 206.90\text{ kJ/kg} \\ v_2 = 0.001004\text{ m}^3\text{/kg} \end{array}$$




(*a*) Using the entropy data from the compressed liquid water table

$$w_P = h_2 - h_1 = 206.90 - 191.81 = \mathbf{15.10\ kJ/kg}$$

(*b*) Using inlet specific volume and pressure values

$$w_P = v_1(P_2 - P_1) = (0.001010\text{ m}^3\text{/kg})(15{,}000 - 10)\text{kPa} = \mathbf{15.14\ kJ/kg}$$

Error = **0.3%**

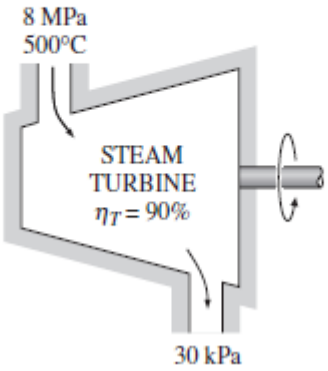
(*b*) Using average specific volume and pressure values

$$w_P = v_{avg}(P_2 - P_1) = \left[1/2(0.001010 + 0.001004)\text{ m}^3\text{/kg}\right](15{,}000 - 10)\text{kPa} = \mathbf{15.10\ kJ/kg}$$

Error = **0%**

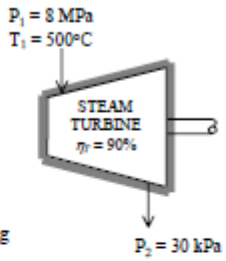
***Discussion*** The results show that any of the method may be used to calculate reversible pump work.

**7–104** Steam enters an adiabatic turbine at 8 MPa and 500°C with a mass flow rate of 3 kg/s and leaves at 30 kPa. The isentropic efficiency of the turbine is 0.90. Neglecting




**7-104** Steam enters an adiabatic turbine with an isentropic efficiency of 0.90 at a specified state with a specified mass flow rate, and leaves at a specified pressure. The turbine exit temperature and power output of the turbine 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** The device is adiabatic and thus heat transfer is negligible.




***Analysis*** (*a*) From the steam tables (Tables A-4 through A-6),

$$\left.\begin{array}{l} P_1 = 8\text{ MPa} \\ T_1 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3399.5\text{ kJ/kg} \\ s_1 = 6.7266\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_{2s} = 30\text{ kPa} \\ s_{2s} = s_1 \end{array}\right\} \begin{array}{l} x_{2s} = \dfrac{s_{2s} - s_f}{s_{fg}} = \dfrac{6.7266 - 0.9441}{6.8234} = 0.8475 \\ h_{2s} = h_f + x_{2s}h_{fg} = 289.27 + (0.8475)(2335.3) = 2268.3\text{ kJ/kg} \end{array}$$

From the isentropic efficiency relation,

$$\eta_T = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \longrightarrow h_{2a} = h_1 - \eta_T(h_1 - h_{2s}) = 3399.5 - (0.9)(3399.5 - 2268.3) = 2381.4\text{ kJ/kg}$$

Thus,

$$\left.\begin{array}{l} P_{2a} = 30\text{ kPa} \\ h_{2a} = 2381.4\text{ kJ/kg} \end{array}\right\} T_{2a} = T_{\text{sat@30 kPa}} = \mathbf{69.09°C}$$

(*b*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual 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

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

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

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

$$\dot{W}_{a,out} = \dot{m}(h_1 - h_2)$$

Substituting,

$$\dot{W}_{a,out} = (3\text{ kg/s})(3399.5 - 2381.4)\text{ kJ/kg} = \mathbf{3054\ kW}$$

**7–106** Steam enters an adiabatic turbine at 7 MPa, 600°C, and 80 m/s and leaves at 50 kPa, 150°C, and 140 m/s. If the power output of the turbine is 6 MW, determine (*a*) the mass flow rate of the steam flowing through the turbine and (*b*) the isentropic efficiency of the turbine. *Answers:* (*a*) 6.95 kg/s, (*b*) 73.4 percent

**7-106** Steam enters an adiabatic turbine at a specified state, and leaves at a specified state. The mass flow rate of the steam and the isentropic efficiency 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 device is adiabatic and thus heat transfer is negligible.

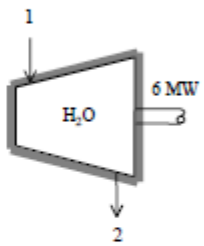
***Analysis*** (*a*) From the steam tables (Tables A-4 and A-6),

$$\left.\begin{array}{l} P_1 = 7\text{ MPa} \\ T_1 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3650.6\text{ kJ/kg} \\ s_1 = 7.0910\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 50\text{ kPa} \\ T_2 = 150°\text{C} \end{array}\right\} h_{2a} = 2780.2\text{ kJ/kg}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual 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

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




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

$$\dot{m}(h_1 + V_1^2/2) = \dot{W}_{a,out} + \dot{m}(h_2 + V_1^2/2) \quad (\text{since } \dot{Q} \cong \Delta pe \cong 0)$$

$$\dot{W}_{a,out} = -\dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}\right)$$

Substituting, the mass flow rate of the steam is determined to be

$$6000\text{ kJ/s} = -\dot{m}\left(2780.2 - 3650.6 + \frac{(140\text{ m/s})^2 - (80\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right)$$

$$\dot{m} = \mathbf{6.95\ kg/s}$$

(*b*) The isentropic exit enthalpy of the steam and the power output of the isentropic turbine are

$$\left.\begin{array}{l} P_{2s} = 50\text{ kPa} \\ s_{2s} = s_1 \end{array}\right\} \begin{array}{l} x_{2s} = \dfrac{s_{2s} - s_f}{s_{fg}} = \dfrac{7.0910 - 1.0912}{6.5019} = 0.9228 \\ h_{2s} = h_f + x_{2s}h_{fg} = 340.54 + (0.9228)(2304.7) = 2467.3\text{ kJ/kg} \end{array}$$

and

$$\dot{W}_{s,out} = -\dot{m}\left(h_{2s} - h_1 + \left(V_2^2 - V_1^2\right)/2\right)$$

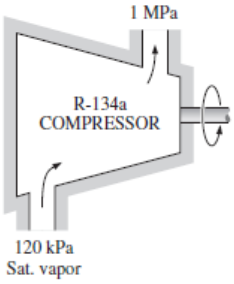
$$\dot{W}_{s,out} = -(6.95\text{ kg/s})\left(2467.3 - 3650.6 + \frac{(140\text{ m/s})^2 - (80\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right)$$

$$= 8174\text{ kW}$$

Then the isentropic efficiency of the turbine becomes

$$\eta_T = \frac{\dot{W}_a}{\dot{W}_s} = \frac{6000\text{ kW}}{8174\text{ kW}} = 0.734 = \mathbf{73.4\%}$$

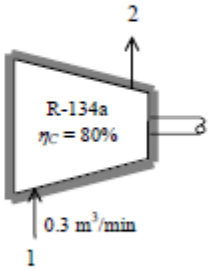
**7–109** Refrigerant-134a enters an adiabatic compressor as saturated vapor at 120 kPa at a rate of 0.3 m³/min and exits at 1-MPa pressure. If the isentropic efficiency of the compressor is 80 percent, determine (*a*) the temperature of the refrigerant at the exit of the compressor and (*b*) the power input, in kW. Also, show the process on a *T-s* diagram with respect to saturation lines.




**7-109** [*Also solved by EES on enclosed CD*] Refrigerant-134a enters an adiabatic compressor with an isentropic efficiency of 0.80 at a specified state with a specified volume flow rate, and leaves at a specified pressure. The compressor exit temperature and power input to the compressor 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** The device is adiabatic and thus heat transfer is negligible.

*Analysis* (a) From the refrigerant tables (Tables A-11E through A-13E),




$$\left.\begin{array}{l} P_1 = 120\text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_1 = h_{g@120\text{ kPa}} = 236.97\text{ kJ/kg} \\ s_1 = s_{g@120\text{ kPa}} = 0.94779\text{ kJ/kg}\cdot\text{K} \\ v_1 = v_{g@120\text{ kPa}} = 0.16212\text{ m}^3\text{/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1\text{ MPa} \\ s_{2s} = s_1 \end{array}\right\} h_{2s} = 281.21\text{ kJ/kg}$$

From the isentropic efficiency relation,

$$\eta_C = \frac{h_{2s} - h_1}{h_{2a} - h_1} \longrightarrow h_{2a} = h_1 + (h_{2s} - h_1)/\eta_C = 236.97 + (281.21 - 236.97)/0.80 = 292.26\text{ kJ/kg}$$

Thus,

$$\left.\begin{array}{l} P_{2a} = 1\text{ MPa} \\ h_{2a} = 292.26\text{ kJ/kg} \end{array}\right\} T_{2a} = 58.9°\text{C}$$

(b) The mass flow rate of the refrigerant is determined from

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{0.3/60\text{ m}^3\text{/s}}{0.16212\text{ m}^3\text{/kg}} = 0.0308\text{ kg/s}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual compressor as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed as

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

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

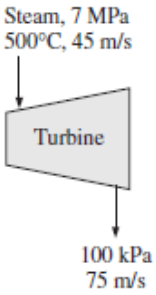
$$\dot{W}_{a,in} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \dot{Q} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

$$\dot{W}_{a,in} = \dot{m}(h_2 - h_1)$$

Substituting, the power input to the compressor becomes,

$$\dot{W}_{a,in} = (0.0308\text{ kg/s})(292.26 - 236.97)\text{kJ/kg} = \mathbf{1.70\ kW}$$

**7–119** Steam enters an adiabatic turbine steadily at 7 MPa, 500°C, and 45 m/s, and leaves at 100 kPa and 75 m/s. If the power output of the turbine is 5 MW and the isentropic efficiency is 77 percent, determine (*a*) the mass flow rate of steam through the turbine, (*b*) the temperature at the turbine exit, and (*c*) the rate of entropy generation during this process.




**7-106** Steam enters an adiabatic turbine at a specified state, and leaves at a specified state. The mass flow rate of the steam and the isentropic efficiency 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 device is adiabatic and thus heat transfer is negligible.

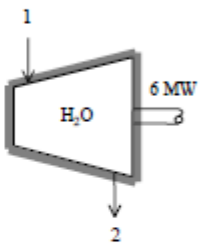
***Analysis*** (*a*) From the steam tables (Tables A-4 and A-6),

$$\left.\begin{array}{l} P_1 = 7\text{ MPa} \\ T_1 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3650.6\text{ kJ/kg} \\ s_1 = 7.0910\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 50\text{ kPa} \\ T_2 = 150°\text{C} \end{array}\right\} h_{2a} = 2780.2\text{ kJ/kg}$$

There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual 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

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




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

$$\dot{m}(h_1 + V_1^2/2) = \dot{W}_{a,out} + \dot{m}(h_2 + V_1^2/2) \quad (\text{since } \dot{Q} \approx \Delta pe \approx 0)$$

$$\dot{W}_{a,out} = -\dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}\right)$$

Substituting, the mass flow rate of the steam is determined to be

$$6000\text{ kJ/s} = -\dot{m}\left(2780.2 - 3650.6 + \frac{(140\text{ m/s})^2 - (80\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right)$$

$$\dot{m} = \mathbf{6.95\ kg/s}$$

(*b*) The isentropic exit enthalpy of the steam and the power output of the isentropic turbine are

$$\left.\begin{array}{l} P_{2s} = 50\text{ kPa} \\ s_{2s} = s_1 \end{array}\right\} \begin{array}{l} x_{2s} = \dfrac{s_{2s} - s_f}{s_{fg}} = \dfrac{7.0910 - 1.0912}{6.5019} = 0.9228 \\ h_{2s} = h_f + x_{2s}h_{fg} = 340.54 + (0.9228)(2304.7) = 2467.3\text{ kJ/kg} \end{array}$$

and

$$\dot{W}_{s,out} = -\dot{m}\left(h_{2s} - h_1 + \left(V_2^2 - V_1^2\right)/2\right)$$

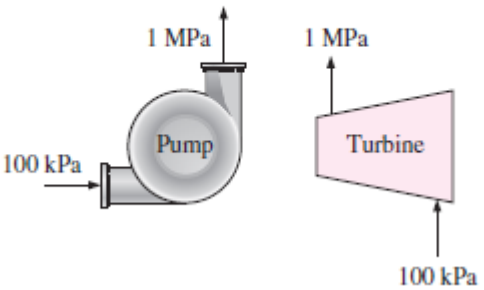
$$\dot{W}_{s,out} = -(6.95\text{ kg/s})\left(2467.3 - 3650.6 + \frac{(140\text{ m/s})^2 - (80\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)\right)$$

$$= 8174\text{ kW}$$

Then the isentropic efficiency of the turbine becomes

$$\eta_T = \frac{\dot{W}_a}{\dot{W}_s} = \frac{6000\text{ kW}}{8174\text{ kW}} = 0.734 = \mathbf{73.4\%}$$

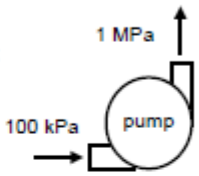
**7–161** Determine the work input and entropy generation during the compression of steam from 100 kPa to 1 MPa in




**7-161** The work input and the entropy generation are to be determined for the compression of saturated liquid water in a pump and that of saturated vapor in a compressor.

***Assumptions*** **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer to or from the fluid is zero.

***Analysis*** Pump Analysis: (Properties are obtained from EES)




$$\left.\begin{array}{l} P_1 = 100\text{ kPa} \\ x_1 = 0\text{ (sat. liq.)} \end{array}\right\} \begin{array}{l} h_1 = 417.51\text{ kJ/kg} \\ s_1 = 1.3028\text{ kJ/kg.K} \end{array} \quad \left.\begin{array}{l} P_2 = 1\text{ MPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 418.45\text{ kJ/kg}$$

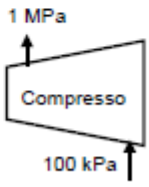
$$h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_P} = 417.51 + \frac{418.45 - 417.51}{0.85} = 418.61\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 1\text{ MPa} \\ h_2 = 418.61\text{ kJ/kg} \end{array}\right\} s_2 = 1.3032\text{ kJ/kg.K}$$

$$w_P = h_2 - h_1 = 418.61 - 417.51 = \mathbf{1.10\text{ kJ/kg}}$$

$$s_{gen,P} = s_2 - s_1 = 1.3032 - 1.3028 = \mathbf{0.0004\text{ kJ/kg.K}}$$

Compressor Analysis:




$$\left.\begin{array}{l} P_1 = 100\text{ kPa} \\ x_1 = 1\text{ (sat. vap.)} \end{array}\right\} \begin{array}{l} h_1 = 2675.0\text{ kJ/kg} \\ s_1 = 7.3589\text{ kJ/kg.K} \end{array} \quad \left.\begin{array}{l} P_2 = 1\text{ MPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 3193.6\text{ kJ/kg}$$

$$h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_C} = 2675.0 + \frac{3193.6 - 2675.0}{0.85} = 3285.1\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 1\text{ MPa} \\ h_2 = 3285.1\text{ kJ/kg} \end{array}\right\} s_2 = 7.4974\text{ kJ/kg.K}$$

$$w_C = h_2 - h_1 = 3285.1 - 2675.0 = \mathbf{610.1\text{ kJ/kg}}$$

$$s_{gen,C} = s_2 - s_1 = 7.4974 - 7.3589 = \mathbf{0.1384\text{ kJ/kg.K}}$$

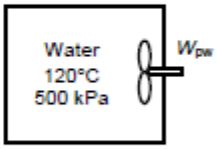
**7–162** A rigid tank contains 1.5 kg of water at 120°C and 500 kPa. Now 22 kJ of shaft work is done on the system and the final temperature in the tank is 95°C. If the entropy change of water is zero and the surroundings are at 15°C, determine (*a*) the final pressure in the tank, (*b*) the amount of heat transfer between the tank and the surroundings, and (*c*) the entropy generation during this process. *Answers:* (*a*) 84.6 kPa, (*b*) 38.5 kJ, (*c*) 0.134 kJ/K

**7-162** A paddle wheel does work on the water contained in a rigid tank. For a zero entropy change of water, the final pressure in the tank, the amount of heat transfer between the tank and the surroundings, and the entropy generation during the process are to be determined.

***Assumptions*** The tank is stationary and the kinetic and potential energy changes are negligible.

***Analysis*** (*a*) Using saturated liquid properties for the compressed liquid at the initial state (Table A-4)

$$\left.\begin{array}{l} T_1 = 120°\text{C} \\ x_1 = 0\ (\text{sat. liq.}) \end{array}\right\} \begin{array}{l} u_1 = 503.60\ \text{kJ/kg} \\ s_1 = 1.5279\ \text{kJ/kg.K} \end{array}$$




The entropy change of water is zero, and thus at the final state we have

$$\left.\begin{array}{l} T_2 = 95°\text{C} \\ s_2 = s_1 = 1.5279\ \text{kJ/kg.K} \end{array}\right\} \begin{array}{l} P_2 = \mathbf{84.6\ kPa} \\ u_2 = 492.63\ \text{kJ/kg} \end{array}$$

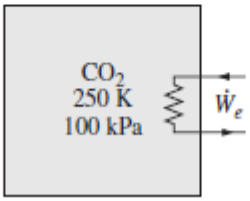
(*b*) The heat transfer can be determined from an energy balance on the tank

$$Q_{out} = W_{Pw,in} - m(u_2 - u_1) = 22\ \text{kJ} - (1.5\ \text{kg})(492.63 - 503.60)\text{kJ/kg} = \mathbf{38.5\ kJ}$$

(*c*) Since the entropy change of water is zero, the entropy generation is only due to the entropy increase of the surroundings, which is determined from

$$S_{gen} = \Delta S_{surr} = \frac{Q_{out}}{T_{surr}} = \frac{38.5\ \text{kJ}}{(15 + 273)\ \text{K}} = \mathbf{0.134\ kJ/K}$$

**7–164** A 0.8-m$^3$ rigid tank contains carbon dioxide ($CO_2$) gas at 250 K and 100 kPa. A 500-W electric resistance heater placed in the tank is now turned on and kept on for 40 min after which the pressure of $CO_2$ is measured to be 175 kPa. Assuming the surroundings to be at 300 K and using constant specific heats, determine (*a*) the final temperature of $CO_2$, (*b*) the net amount of heat transfer from the tank, and (*c*) the entropy generation during this process.

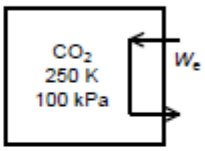



**7-164** An electric resistance heater is doing work on carbon dioxide contained an a rigid tank. The final temperature in the tank, the amount of heat transfer, and the entropy generation are to be determined.

***Assumptions*** **1** Kinetic and potential energy changes are negligible. **2** Carbon dioxide is ideal gas with constant specific heats at room temperature.

***Properties*** The properties of $CO_2$ at an anticipated average temperature of 350 K are $R$ = 0.1889 kPa.m$^3$/kg.K, $c_p$ = 0.895 kJ/kg.K, $c_v$ = 0.706 kJ/kg.K (Table A-2b).

***Analysis*** (*a*) The mass and the final temperature of $CO_2$ may be determined from ideal gas equation




$$m = \frac{P_1 V}{RT_1} = \frac{(100\,\text{kPa})(0.8\,\text{m}^3)}{(0.1889\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(250\,\text{K})} = 1.694\,\text{kg}$$

$$T_2 = \frac{P_2 V}{mR} = \frac{(175\,\text{kPa})(0.8\,\text{m}^3)}{(1.694\,\text{kg})(0.1889\,\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = \mathbf{437.5\,K}$$

(*b*) The amount of heat transfer may be determined from an energy balance on the system

$$Q_{out} = \dot{E}_{e,in}\Delta t - mc_v(T_2 - T_1)$$
$$= (0.5\,\text{kW})(40\times 60\,\text{s}) - (1.694\,\text{kg})(0.706\,\text{kJ/kg.K})(437.5 - 250)\text{K} = \mathbf{975.8\ kJ}$$

(*c*) The entropy generation associated with this process may be obtained by calculating total entropy change, which is the sum of the entropy changes of $CO_2$ and the surroundings

$$S_{gen} = \Delta S_{CO2} + \Delta S_{surr} = m\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}\right) + \frac{Q_{out}}{T_{surr}}$$
$$= (1.694\,\text{kg})\left[(0.895\,\text{kJ/kg.K})\ln\frac{437.5\,\text{K}}{250\,\text{K}} - (0.1889\,\text{kJ/kg.K})\ln\frac{175\,\text{kPa}}{100\,\text{kPa}}\right] + \frac{975.8\,\text{kJ}}{300\,\text{K}}$$
$$= \mathbf{3.92\ kJ/K}$$

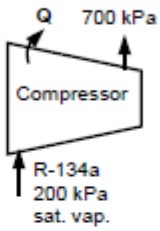
**7–166** Refrigerant-134a enters a compressor as a saturated vapor at 200 kPa at a rate of 0.03 $m^3/s$ and leaves at 700 kPa. The power input to the compressor is 10 kW. If the surroundings at 20°C experience an entropy increase of 0.008 kW/K, determine (*a*) the rate of heat loss from the compressor, (*b*) the exit temperature of the refrigerant, and (*c*) the rate of entropy generation.

**7-166** Refrigerant-134a is compressed in a compressor. The rate of heat loss from the compressor, the exit temperature of R-134a, and the rate of entropy generation are to be determined.

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

***Analysis*** (*a*) The properties of R-134a at the inlet of the compressor are (Table A-12)

$$\left.\begin{array}{l} P_1 = 200\text{ kPa} \\ x_1 = 1 \end{array}\right\} \begin{array}{l} v_1 = 0.09987\text{ m}^3/\text{kg} \\ h_1 = 244.46\text{ kJ/kg} \\ s_1 = 0.93773\text{ kJ/kg.K} \end{array}$$




The mass flow rate of the refrigerant is

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{0.03\text{ m}^3/\text{s}}{0.09987\text{ m}^3/\text{kg}} = 0.3004\text{ kg/s}$$

Given the entropy increase of the surroundings, the heat lost from the compressor is

$$\Delta\dot{S}_{surr} = \frac{\dot{Q}_{out}}{T_{surr}} \longrightarrow \dot{Q}_{out} = T_{surr}\Delta\dot{S}_{surr} = (20 + 273\text{ K})(0.008\text{ kW/K}) = \mathbf{2.344\ kW}$$

(*b*) An energy balance on the compressor gives

$$\dot{W}_{in} - \dot{Q}_{out} = \dot{m}(h_2 - h_1)$$

$$10\text{ kW} - 2.344\text{ kW} = (0.3004\text{ kg/s})(h_2 - 244.46)\text{ kJ/kg} \longrightarrow h_2 = 269.94\text{ kJ/kg}$$

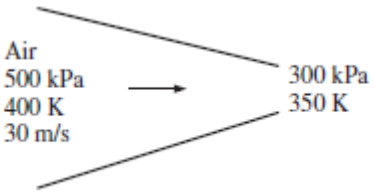
The exit state is now fixed. Then,

$$\left.\begin{array}{l} P_2 = 700\text{ kPa} \\ h_2 = 269.94\text{ kJ/kg} \end{array}\right\} \begin{array}{l} \mathbf{T_2 = 31.5°C} \\ s_2 = 0.93620\text{ kJ/kg.K} \end{array}$$

(*c*) The entropy generation associated with this process may be obtained by adding the entropy change of R-134a as it flows in the compressor and the entropy change of the surroundings

$$\begin{aligned} \dot{S}_{gen} &= \Delta\dot{S}_R + \Delta\dot{S}_{surr} = \dot{m}(s_2 - s_1) + \Delta\dot{S}_{surr} \\ &= (0.3004\text{ kg/s})(0.93620 - 0.93773)\text{ kJ/kg.K} + 0.008\text{ kW/K} \\ &= \mathbf{0.00754\ kJ/K} \end{aligned}$$

**7–167** Air at 500 kPa and 400 K enters an adiabatic nozzle at a velocity of 30 m/s and leaves at 300 kPa and 350 K. Using variable specific heats, determine (*a*) the isentropic efficiency, (*b*) the exit velocity, and (*c*) the entropy generation.




**7-167** Air flows in an adiabatic nozzle. The isentropic efficiency, the exit velocity, and the entropy generation are to be determined.

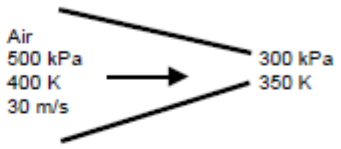
***Properties*** The gas constant of air is $R = 0.287$ kJ/kg.K (Table A-1).

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

***Analysis*** (*a*) (*b*) Using variable specific heats, the properties can be determined from air table as follows

$$T_1 = 400\text{ K} \longrightarrow \begin{cases} h_1 = 400.98\text{ kJ/kg} \\ s_1^0 = 1.99194\text{ kJ/kg.K} \\ P_{r1} = 3.806 \end{cases}$$

$$T_2 = 350\text{ K} \longrightarrow \begin{cases} h_2 = 350.49\text{ kJ/kg} \\ s_2^0 = 1.85708\text{ kJ/kg.K} \end{cases}$$




$$P_{r2} = \frac{P_2}{P_1}P_{r1} = \frac{300\text{ kPa}}{500\text{ kPa}}(3.806) = 2.2836 \longrightarrow h_{2s} = 346.31\text{ kJ/kg}$$

Energy balances on the control volume for the actual and isentropic processes give

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

$$400.98\text{ kJ/kg} + \frac{(30\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 350.49\text{ kJ/kg} + \frac{V_2^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)$$

$$V_2 = \mathbf{319.1\text{ m/s}}$$

$$h_1 + \frac{V_1^2}{2} = h_{2s} + \frac{V_{2s}^2}{2}$$

$$400.98\text{ kJ/kg} + \frac{(30\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 346.31\text{ kJ/kg} + \frac{V_{2s}^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right)$$

$$V_{2s} = 331.8\text{ m/s}$$

The isentropic efficiency is determined from its definition,

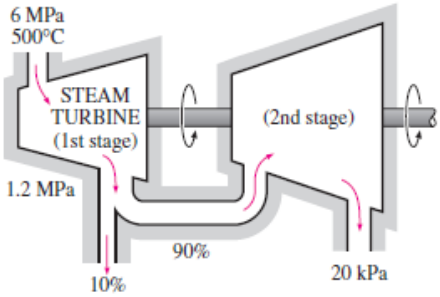
$$\eta_N = \frac{V_2^2}{V_{2s}^2} = \frac{(319.1\text{ m/s})^2}{(331.8\text{ m/s})^2} = \mathbf{0.925}$$

(*c*) Since the nozzle is adiabatic, the entropy generation is equal to the entropy increase of the air as it flows in the nozzle

$$s_{gen} = \Delta s_{air} = s_2^0 - s_1^0 - R\ln\frac{P_2}{P_1}$$

$$= (1.85708 - 1.99194)\text{kJ/kg.K} - (0.287\text{ kJ/kg.K})\ln\frac{300\text{ kPa}}{500\text{ kPa}} = \mathbf{0.0118\text{ kJ/kg.K}}$$

**7–175** Steam at 6 MPa and 500°C enters a two-stage adiabatic turbine at a rate of 15 kg/s. Ten percent of the steam is extracted at the end of the first stage at a pressure of 1.2 MPa for other use. The remainder of the steam is further expanded in the second stage and leaves the turbine at 20 kPa. Determine the power output of the turbine, assuming (*a*) the process is reversible and (*b*) the turbine has an isentropic efficiency of 88 percent. *Answers:* (*a*) 16,291 kW, (*b*) 14,336 kW




**7-175** Steam expands in a two-stage adiabatic turbine from a specified state to specified pressure. Some steam is extracted at the end of the first stage. The power output of the turbine is to be determined for the cases of 100% and 88% isentropic efficiencies.

***Assumptions*** **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** The turbine is adiabatic and thus heat transfer is negligible.

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

$$\left.\begin{array}{l} P_1 = 6\text{ MPa} \\ T_1 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3423.1\text{ kJ/kg} \\ s_1 = 6.8826\text{ kJ/kg}\cdot\text{K} \end{array}$$

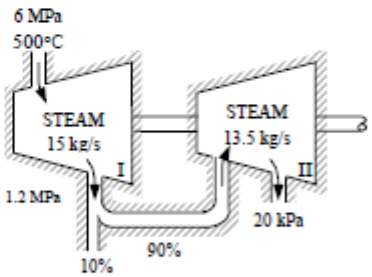
$$\left.\begin{array}{l} P_2 = 1.2\text{ MPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 2962.8\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 20\text{ kPa} \\ s_3 = s_1 \end{array}\right\} \begin{array}{l} x_{3s} = \dfrac{s_{3s} - s_f}{s_{fg}} = \dfrac{6.8826 - 0.8320}{7.0752} = 0.8552 \\ h_{3s} = h_f + x_{3s}h_{fg} = 251.42 + (0.8552)(2357.5) = 2267.5\text{ kJ/kg} \end{array}$$

***Analysis*** (*a*) The mass flow rate through the second stage is

$$\dot{m}_3 = 0.9\dot{m}_1 = (0.9)(15\text{ kg/s}) = 13.5\text{ kg/s}$$

We take the entire turbine, including the connection part between the two stages, as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters the turbine and two fluid streams leave, the energy balance for this steady-flow system can be expressed in the rate form as




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

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

$$\dot{m}_1 h_1 = (\dot{m}_1 - \dot{m}_3)h_2 + \dot{W}_{out} + \dot{m}_3 h_3$$

$$\dot{W}_{out} = \dot{m}_1 h_1 - (\dot{m}_1 - \dot{m}_3)h_2 - \dot{m}_3 h_3$$

$$= \dot{m}_1(h_1 - h_2) + \dot{m}_3(h_2 - h_3)$$

Substituting, the power output of the turbine is

$$\dot{W}_{out} = (15\text{ kg/s})(3423.1 - 2962.8)\text{kJ/kg} + (13.5\text{ kg})(2962.8 - 2267.5)\text{kJ/kg} = \mathbf{16{,}291\ kW}$$

(*b*) If the turbine has an adiabatic efficiency of 88%, then the power output becomes

$$\dot{W}_a = \eta_T \dot{W}_s = (0.88)(16{,}291\text{ kW}) = \mathbf{14{,}336\ kW}$$

**7–176** Steam enters a two-stage adiabatic turbine at 8 MPa and 550°C. It expands in the first stage to a pressure of 2 MPa. Then steam is reheated at constant pressure to 550°C before it is expanded in a second stage to a pressure of 200 kPa. The power output of the turbine is 80 MW. Assuming an isentropic efficiency of 84 percent for each stage of the turbine, determine the required mass flow rate of steam. Also, show the process on a *T-s* diagram with respect to saturation lines. *Answer:* 85.8 kg/s

**7-176** Steam expands in an 84% efficient two-stage adiabatic turbine from a specified state to a specified pressure. Steam is reheated between the stages. For a given power output, the mass flow rate of steam through the turbine is 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** The turbine is adiabatic and thus heat transfer is negligible.

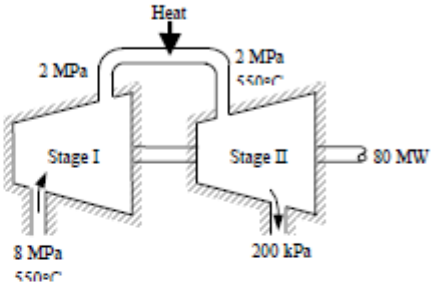
***Properties*** From the steam tables (Tables A-4 through 6)

$$\left.\begin{array}{l} P_1 = 8\text{ MPa} \\ T_1 = 550°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3521.8\text{ kJ/kg} \\ s_1 = 6.8800\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_{2s} = 2\text{ MPa} \\ s_{2s} = s_1 \end{array}\right\} h_{2s} = 3089.7\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 2\text{ MPa} \\ T_3 = 550°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3579.0\text{ kJ/kg} \\ s_3 = 7.5725\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_{4s} = 200\text{ kPa} \\ s_{4s} = s_3 \end{array}\right\} h_{4s} = 2901.7\text{ kJ/kg}$$




***Analysis*** The power output of the actual turbine is given to be 80 MW. Then the power output for the isentropic operation becomes

$$\dot{W}_{s,out} = \dot{W}_{a,out} / \eta_T = (80{,}000\text{ kW})/0.84 = 95{,}240\text{ kW}$$

We take the entire turbine, excluding the reheat section, as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system in isentropic operation can be expressed in the rate form as

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

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

$$\dot{m}h_1 + \dot{m}h_3 = \dot{m}h_{2s} + \dot{m}h_{4s} + \dot{W}_{s,out}$$

$$\dot{W}_{s,out} = \dot{m}[(h_1 - h_{2s}) + (h_3 - h_{4s})]$$

Substituting,

$$95{,}240\text{ kJ/s} = \dot{m}\left[(3521.8 - 3089.7)\text{kJ/kg} + (3579.0 - 2901.7)\text{kJ/kg}\right]$$

which gives

$$\dot{m} = \mathbf{85.8\ kg/s}$$

**7–177** Refrigerant-134a at 140 kPa and −10°C is compressed by an adiabatic 0.7-kW compressor to an exit state of 700 kPa and 50°C. Neglecting the changes in kinetic and potential energies, determine (*a*) the isentropic efficiency of the compressor, (*b*) the volume flow rate of the refrigerant at the compressor inlet, in L/min, and (*c*) the maximum volume flow rate at the inlet conditions that this adiabatic 0.7-kW compressor can handle without violating the second law.

**7-177** Refrigerant-134a is compressed by a 0.7-kW adiabatic compressor from a specified state to another specified state. The isentropic efficiency, the volume flow rate at the inlet, and the maximum flow rate at the compressor inlet are to be determined.

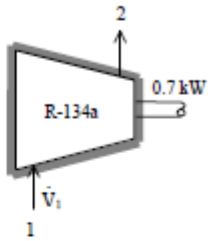
***Assumptions*** **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** The device is adiabatic and thus heat transfer is negligible.

***Properties*** From the R-134a tables (Tables A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 140 \text{ kPa} \\ T_1 = -10°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.14605 \text{ m}^3/\text{kg} \\ h_1 = 246.36 \text{ kJ/kg} \\ s_1 = 0.9724 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 700 \text{ kPa} \\ T_2 = 50°\text{C} \end{array}\right\} h_2 = 288.53 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 700 \text{ kPa} \\ s_{2s} = s_1 \end{array}\right\} h_{2s} = 281.16 \text{ kJ/kg}$$




***Analysis*** (a) The isentropic efficiency is determined from its definition,

$$\eta_C = \frac{h_{2s} - h_1}{h_{2a} - h_1} = \frac{281.16 - 246.36}{288.53 - 246.36} = 0.825 = \mathbf{82.5\%}$$

(*b*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the actual compressor as the system, which is a control volume. The energy balance for this steady-flow system can be expressed as

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

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

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

$$\dot{W}_{a,in} = \dot{m}(h_2 - h_1)$$

Then the mass and volume flow rates of the refrigerant are determined to be

$$\dot{m} = \frac{\dot{W}_{a,in}}{h_{2a} - h_1} = \frac{0.7 \text{ kJ/s}}{(288.53 - 246.36)\text{kJ/kg}} = 0.0166 \text{ kg/s}$$

$$\dot{V}_1 = \dot{m}v_1 = (0.0166 \text{ kg/s})(0.14605 \text{ m}^3/\text{kg}) = 0.00242 \text{ m}^3/\text{s} = \mathbf{145\ L/min}$$

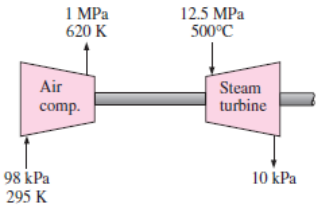
(*c*) The volume flow rate will be a maximum when the process is isentropic, and it is determined similarly from the steady-flow energy equation applied to the isentropic process. It gives

$$\dot{m}_{max} = \frac{\dot{W}_{s,in}}{h_{2s} - h_1} = \frac{0.7 \text{ kJ/s}}{(281.16 - 246.36)\text{kJ/kg}} = 0.0201 \text{ kg/s}$$

$$\dot{V}_{1,max} = \dot{m}_{max}v_1 = (0.0201 \text{ kg/s})(0.14605 \text{ m}^3/\text{kg}) = 0.00294 \text{ m}^3/\text{s} = \mathbf{176\ L/min}$$

***Discussion*** Note that the raising the isentropic efficiency of the compressor to 100% would increase the volumetric flow rate by more than 20%.

**7–179** An adiabatic air compressor is to be powered by a direct-coupled adiabatic steam turbine that is also driving a generator. Steam enters the turbine at 12.5 MPa and 500°C at a rate of 25 kg/s and exits at 10 kPa and a quality of 0.92. Air enters the compressor at 98 kPa and 295 K at a rate of 10 kg/s and exits at 1 MPa and 620 K. Determine (*a*) the net power delivered to the generator by the turbine and (*b*) the rate of entropy generation within the turbine and the compressor during this process.




**7-179** [*Also solved by EES on enclosed CD*] An adiabatic compressor is powered by a direct-coupled steam turbine, which also drives a generator. The net power delivered to the generator and the rate of entropy generation 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** The devices are adiabatic and thus heat transfer is negligible. **4** Air is an ideal gas with variable specific heats.

***Properties*** The gas constant of air is $R = 0.287$ kJ/kg.K (Table A-1). From the steam tables (Tables A-4 through 6) and air table (Table A-17),

$$T_1 = 295\text{ K} \longrightarrow h_1 = 295.17\text{ kJ/kg},\ s_1^\circ = 1.68515\text{ kJ/kg}\cdot\text{K}$$

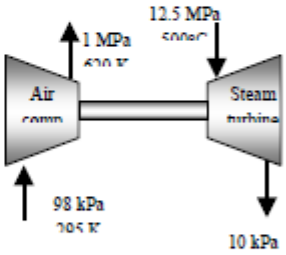
$$T_2 = 620\text{ K} \longrightarrow h_2 = 628.07\text{ kJ/kg},\ s_2^\circ = 2.44356\text{ kJ/kg}\cdot\text{K}$$

$$\left.\begin{array}{l} P_3 = 12.5\text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} \begin{array}{l} h_3 = 3343.6\text{ kJ/kg} \\ s_3 = 6.4651\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 10\text{ kPa} \\ x_4 = 0.92 \end{array}\right\} \begin{array}{l} h_4 = h_f + x_4 h_{fg} = 191.81 + (0.92)(2392.1) = 2392.5\text{ kJ/kg} \\ s_4 = s_f + x_4 s_{fg} = 0.6492 + (0.92)(7.4996) = 7.5489\text{ kJ/kg}\cdot\text{K} \end{array}$$

***Analysis*** There is only one inlet and one exit for either device, and thus $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$. We take either the turbine or the compressor as the system, which is a control volume since mass crosses the boundary. The energy balance for either steady-flow system can be expressed in the rate form as

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




For the turbine and the compressor it becomes

Compressor: $\dot{W}_{comp,in} + \dot{m}_{air} h_1 = \dot{m}_{air} h_2 \rightarrow \dot{W}_{comp,in} = \dot{m}_{air}(h_2 - h_1)$

Turbine: $\dot{m}_{steam} h_3 = \dot{W}_{turb,out} + \dot{m}_{steam} h_4 \rightarrow \dot{W}_{turb,out} = \dot{m}_{steam}(h_3 - h_4)$

Substituting,

$$\dot{W}_{comp,in} = (10\text{ kg/s})(628.07 - 295.17)\text{kJ/kg} = 3329\text{ kW}$$

$$\dot{W}_{turb,out} = (25\text{ kg/s})(3343.6 - 2392.5)\text{kJ/kg} = 23{,}777\text{ kW}$$

Therefore, $\dot{W}_{net,out} = \dot{W}_{turb,out} - \dot{W}_{comp,in} = 23{,}777 - 3329 = \mathbf{20{,}448\ kW}$

Noting that the system is adiabatic, the total rate of entropy change (or generation) during this process is the sum of the entropy changes of both fluids,

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

where

$$\dot{m}_{air}(s_2 - s_1) = \dot{m}\left(s_2^\circ - s_1^\circ - R\ln\frac{P_2}{P_1}\right)$$

$$= (10\text{ kg/s})\left(2.44356 - 1.68515 - 0.287\ln\frac{1000\text{ kPa}}{98\text{ kPa}}\right)\text{kJ/kg}\cdot\text{K} = 0.92\text{ kW/K}$$

$$\dot{m}_{steam}(s_4 - s_3) = (25\text{ kg/s})(7.5489 - 6.4651)\text{kJ/kg}\cdot\text{K} = 27.1\text{ kW/K}$$

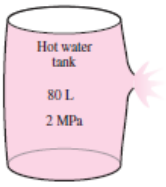
Substituting, the total rate of entropy generation is determined to be

$$\dot{S}_{gen,total} = \dot{S}_{gen,comp} + \dot{S}_{gen,turb} = 0.92 + 27.1 = \mathbf{28.02\ kW/K}$$

**7–182** The explosion of a hot water tank in a school in Spencer, Oklahoma, in 1982 killed 7 people while injuring 33 others. Although the number of such explosions has decreased dramatically since the development of the ASME Pressure Vessel Code, which requires the tanks to be designed to withstand four times the normal operating pressures, they still occur as a result of the failure of the pressure relief valves and thermostats. When a tank filled with a high-pressure and high-temperature liquid ruptures, the sudden drop of the pressure of the liquid to the atmospheric level causes part of the liquid to flash into vapor, and thus to experience a huge rise in its volume. The resulting pressure wave that propagates rapidly can cause considerable damage.

Considering that the pressurized liquid in the tank eventually reaches equilibrium with its surroundings shortly after the explosion, the work that a pressurized liquid would do if allowed to expand reversibly and adiabatically to the pressure of the surroundings can be viewed as the *explosive energy* of the pressurized liquid. Because of the very short time period of the explosion and the apparent calm afterward, the explosion process can be considered to be adiabatic with no changes in kinetic and potential energies and no mixing with the air.

Consider a 80-L hot-water tank that has a working pressure of 0.5 MPa. As a result of some malfunction, the pressure in the tank rises to 2 MPa, at which point the tank explodes. Taking the atmospheric pressure to be 100 kPa and assuming the liquid in the tank to be saturated at the time of explosion, determine the total explosion energy of the tank in terms of the TNT equivalence. (The explosion energy of TNT is about 3250 kJ/kg, and 5 kg of TNT can cause total destruction of unreinforced structures within about a 7-m radius.) *Answer:* 1.972 kg TNT

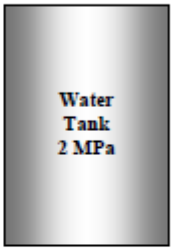


**7-182** The pressure in a hot water tank rises to 2 MPa, and the tank explodes. The explosion energy of the water is to be determined, and expressed in terms of its TNT equivalence.

***Assumptions*** **1** The expansion process during explosion is isentropic. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer with the surroundings during explosion is negligible.

***Properties*** The explosion energy of TNT is 3250 kJ/kg. From the steam tables (Tables A-4 through 6)

$$\left.\begin{array}{l} P_1 = 2\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} v_1 = v_{f@2\text{ MPa}} = 0.001177\text{ m}^3/\text{kg} \\ u_1 = u_{f@2\text{ MPa}} = 906.12\text{ kJ/kg} \\ s_1 = s_{f@2\text{ MPa}} = 2.4467\text{ kJ/kg}\cdot\text{K} \end{array}$$




$$\left.\begin{array}{l} P_2 = 100\text{ kPa} \\ s_2 = s_1 \end{array}\right\} \begin{array}{l} u_f = 417.40, \quad u_{fg} = 2088.2\text{ kJ/kg} \\ s_f = 1.3028, \quad s_{fg} = 6.0562\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{2.4467 - 1.3028}{6.0562} = 0.1889$$

$$u_2 = u_f + x_2 u_{fg} = 417.40 + (0.1889)(2088.2) = 811.83\text{ kJ/kg}$$

***Analysis*** We idealize the water tank as a closed system that undergoes a reversible adiabatic process with negligible changes in kinetic and potential energies. The work done during this idealized process represents the explosive energy of the tank, and is determined from the closed system energy balance to be

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

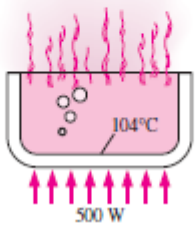
$$-W_{b,out} = \Delta U = m(u_2 - u_1)$$

$$E_{exp} = W_{b,out} = m(u_1 - u_2)$$

where $$m = \frac{V}{v_1} = \frac{0.080\text{ m}^3}{0.001177\text{ m}^3/\text{kg}} = 67.99\text{ kg}$$

Substituting, $$E_{exp} = (67.99\text{ kg})(906.12 - 811.83)\text{kJ/kg} = 6410\text{ kJ}$$

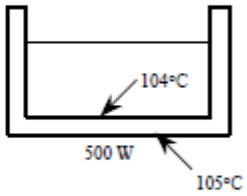
**7–187** Heat is transferred steadily to boiling water in the pan through its flat bottom at a rate of 500 W. If the temperatures of the inner and outer surfaces of the bottom of the tank are 104°C and 105°C, respectively, determine the rate of entropy generation within bottom of the pan, in W/K.



**7-187** Heat is transferred steadily to boiling water in a pan through its bottom. The rate of entropy generation within the bottom plate is to be determined.

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

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




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

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

$$\frac{500\text{ W}}{378\text{ K}} - \frac{500\text{ W}}{377\text{ K}} + \dot{S}_{gen,system} = 0 \quad \rightarrow \quad \dot{S}_{gen,system} = \mathbf{0.00351\ W/K}$$

***Discussion*** Note that there is a small temperature drop across the bottom of the pan, and thus a small amount of entropy generation.

**7–188** A 1200-W electric resistance heating element whose diameter is 0.5 cm is immersed in 40 kg of water initially at 20°C. Assuming the water container is well-insulated, determine how long it will take for this heater to raise the water temperature to 50°C. Also, determine the entropy generated during this process, in kJ/K.

**7-188** An electric resistance heater is immersed in water. The time it will take for the electric heater to raise the water temperature to a specified temperature and the entropy generated during this process are to be determined.

***Assumptions*** **1** Water is an incompressible substance with constant specific heats. **2** The energy stored in the container itself and the heater is negligible. **3** Heat loss from the container is negligible.

***Properties*** The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3).

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

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

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

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

Substituting,

$$(1200 \text{ J/s})\Delta t = (40 \text{ kg})(4180 \text{ J/kg·°C})(50 - 20)\text{°C}$$

Solving for $\Delta t$ gives

$$\Delta t = \mathbf{4180 \text{ s} = 69.7 \text{ min} = 1.16 \text{ h}}$$

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

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

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

Therefore, the entropy generated during this process is

$$S_{gen} = \Delta S_{water} = mc\ln\frac{T_2}{T_1} = (40 \text{ kg})(4.18 \text{ kJ/kg·K})\ln\frac{323 \text{ K}}{293 \text{ K}} = \mathbf{16.3 \text{ kJ/K}}$$

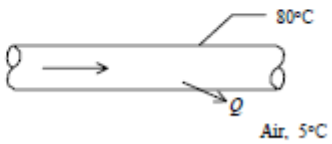
**7–189** A hot-water pipe at 80°C is losing heat to the surrounding air at 5°C at a rate of 2200 W. Determine the rate of entropy generation in the surrounding air, in W/K.

**7-189** A hot water pipe at a specified temperature is losing heat to the surrounding air at a specified rate. The rate of entropy generation in the surrounding air due to this heat transfer are to be determined.

***Assumptions*** Steady operating conditions exist.

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

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




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

$$\frac{2200 \text{ W}}{353 \text{ K}} - \frac{2200 \text{ W}}{278 \text{ K}} + \dot{S}_{gen,system} = 0 \quad \rightarrow \quad \dot{S}_{gen,system} = \mathbf{1.68 \text{ W/K}}$$

**7–190** In large steam power plants, the feedwater is frequently heated in closed feedwater heaters, which are basically heat exchangers, by steam extracted from the turbine at some stage. Steam enters the feedwater heater at 1 MPa and 200°C and leaves as saturated liquid at the same pressure. Feedwater enters the heater at 2.5 MPa and 50°C and leaves 10°C below the exit temperature of the steam. Neglecting any heat losses from the outer surfaces of the heater, determine (*a*) the ratio of the mass flow rates of the extracted steam and the feedwater heater and (*b*) the total entropy change for this process per unit mass of the feedwater.

**7-190** The feedwater of a steam power plant is preheated using steam extracted from the turbine. The ratio of the mass flow rates of the extracted steam to the feedwater and entropy generation per unit mass of feedwater 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 Heat loss from the device to the surroundings is negligible.

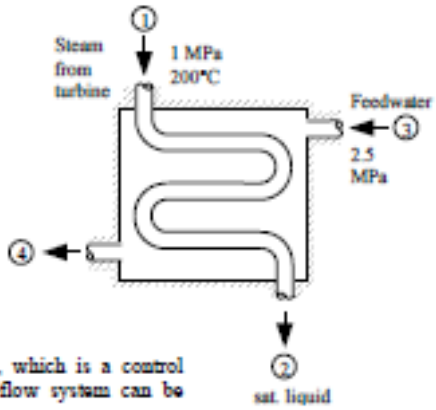
*Properties* The properties of steam and feedwater are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 1\text{ MPa} \\ T_1 = 200^\circ\text{C} \end{array}\right\} \begin{array}{l} h_1 = 2828.3\text{ kJ/kg} \\ s_1 = 6.6956\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 1\text{ MPa} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_2 = h_{f@1\text{ MPa}} = 762.51\text{ kJ/kg} \\ s_2 = s_{f@1\text{ MPa}} = 2.1381\text{ kJ/kg}\cdot\text{K} \\ T_2 = 179.88^\circ\text{C} \end{array}$$

$$\left.\begin{array}{l} P_3 = 2.5\text{ MPa} \\ T_3 = 50^\circ\text{C} \end{array}\right\} \begin{array}{l} h_3 \cong h_{f@50^\circ\text{C}} = 209.34\text{ kJ/kg} \\ s_3 \cong s_{f@50^\circ\text{C}} = 0.7038\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 2.5\text{ MPa} \\ T_4 = T_2 - 10^\circ\text{C} \cong 170^\circ\text{C} \end{array}\right\} \begin{array}{l} h_4 \cong h_{f@170^\circ\text{C}} = 719.08\text{ kJ/kg} \\ s_4 \cong s_{f@170^\circ\text{C}} = 2.0417\text{ kJ/kg}\cdot\text{K} \end{array}$$




*Analysis* (*a*) We take the heat exchanger 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 follows:

*Mass balance* (for each fluid stream):

$$\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system}^{\nearrow 0\text{ (steady)}} = 0 \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_s \quad \text{and} \quad \dot{m}_3 = \dot{m}_4 = \dot{m}_{fw}$$

*Energy balance* (for the heat exchanger):

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

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

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} = \dot{W} = \Delta ke \cong \Delta pe \cong 0)$$

Combining the two, $\dot{m}_s(h_2 - h_1) = \dot{m}_{fw}(h_3 - h_4)$

Dividing by $\dot{m}_{fw}$ and substituting, $\dfrac{\dot{m}_s}{\dot{m}_{fw}} = \dfrac{h_4 - h_3}{h_1 - h_2} = \dfrac{(719.08 - 209.34)\text{ kJ/kg}}{(2828.3 - 762.51)\text{ kJ/kg}} = \mathbf{0.247}$

(*b*) The total entropy change (or entropy generation) during this process per unit mass of feedwater can be determined from an entropy balance expressed in the rate form as

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

$$\dot{m}_1 s_1 - \dot{m}_2 s_2 + \dot{m}_3 s_3 - \dot{m}_4 s_4 + \dot{S}_{gen} = 0$$

$$\dot{m}_s(s_1 - s_2) + \dot{m}_{fw}(s_3 - s_4) + \dot{S}_{gen} = 0$$

$$\frac{\dot{S}_{gen}}{\dot{m}_{fw}} = \frac{\dot{m}_s}{\dot{m}_{fw}}(s_2 - s_1) + (s_4 - s_3) = (0.247)(2.1381 - 6.6956) + (2.0417 - 0.7038)$$

$$= \mathbf{0.213}\text{ kJ/K per kg of feedwater}$$

**7–196** A passive solar house that is losing heat to the outdoors at 3°C at an average rate of 50,000 kJ/h is maintained at 22°C at all times during a winter night for 10 h. The house is to be heated by 50 glass containers, each containing 20 L of water that is heated to 80°C during the day by absorbing solar energy. A thermostat controlled 15 kW backup electric resistance heater turns on whenever necessary to keep the house at 22°C. Determine how long the electric heating system was on that night and the amount of entropy generated during the night.

**7-196** The heating of a passive solar house at night is to be assisted by solar heated water. The length of time that the electric heating system would run that night and the amount of entropy generated that night are to be determined.

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

***Properties*** The density and specific heat of water at room temperature are $\rho$ = 1 kg/L and $c$ = 4.18 kJ/kg·°C (Table A-3).

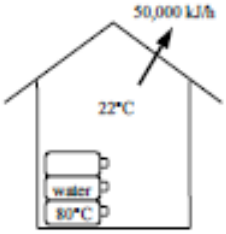
***Analysis*** The total mass of water is

$$m_w = \rho V = (1\ \text{kg/L})(50 \times 20\ \text{L}) = 1000\ \text{kg}$$

Taking the contents of the house, including the water as our system, the energy balance relation can be written as

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

$$W_{e,in} - Q_{out} = \Delta U = (\Delta U)_{water} + (\Delta U)_{air}$$
$$= (\Delta U)_{water}$$
$$= mc(T_2 - T_1)_{water}$$




or,

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

Substituting,

$$(15\ \text{kJ/s})\Delta t - (50{,}000\ \text{kJ/h})(10\ \text{h}) = (1000\ \text{kg})(4.18\ \text{kJ/kg·°C})(22 - 80)\text{°C}$$

It gives

$$\Delta t = 17{,}170\ \text{s} = \mathbf{4.77\ h}$$

We take the house as the system, which is a closed system. The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the house 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 the extended system can be expressed as

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

$$-\frac{Q_{out}}{T_{b,out}} + S_{gen} = \Delta S_{water} + \Delta S_{air}^{\,\nearrow 0} = \Delta S_{water}$$

since the state of air in the house remains unchanged. Then the entropy generated during the 10-h period that night is

$$S_{gen} = \Delta S_{water} + \frac{Q_{out}}{T_{b,out}} = \left(mc\ln\frac{T_2}{T_1}\right)_{water} + \frac{Q_{out}}{T_{surr}}$$
$$= (1000\ \text{kg})(4.18\ \text{kJ/kg·K})\ln\frac{295\ \text{K}}{353\ \text{K}} + \frac{500{,}000\ \text{kJ}}{276\ \text{K}}$$
$$= -750 + 1811 = \mathbf{1061\ kJ/K}$$

**7–198** Air enters the evaporator section of a window air conditioner at 100 kPa and 27°C with a volume flow rate of 6 m³/min. The refrigerant-134a at 120 kPa with a quality of 0.3 enters the evaporator at a rate of 2 kg/min and leaves as saturated vapor at the same pressure. Determine the exit temperature of the air and the rate of entropy generation for this process, assuming (*a*) the outer surfaces of the air conditioner are insulated and (*b*) heat is transferred to the evaporator of the air conditioner from the surrounding medium at 32°C at a rate of 30 kJ/min. *Answers:* (*a*) −15.9°C, 0.00193 kW/K, (*b*) −11.6°C, 0.00223 kW/K

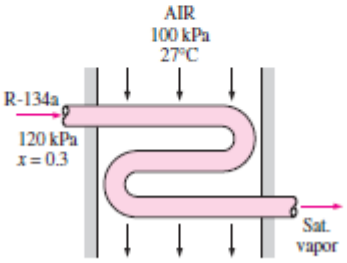



**FIGURE P7–198**

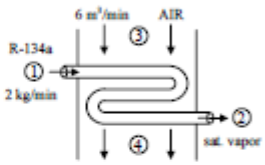
**7-198** Refrigerant-134a is vaporized by air in the evaporator of an air-conditioner. For specified flow rates, the exit temperature of air and the rate of entropy generation are to be determined for the cases of an insulated and uninsulated evaporator.

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

*Properties* The gas constant of air is 0.287 kPa.m³/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). The properties of R-134a at the inlet and the exit states are (Tables A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 120\text{ kPa} \\ x_1 = 0.3 \end{array}\right\} \begin{array}{l} h_1 = h_f + x_1 h_{fg} = 22.49 + 0.3 \times 214.48 = 86.83\text{ kJ/kg} \\ s_1 = s_f + x_1 s_{fg} = 0.09275 + 0.3(0.85503) = 0.3493\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_2 = 120\text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_2 = h_{g@120\text{ kPa}} = 236.97\text{ kJ/kg} \\ s_2 = h_{g@120\text{ kPa}} = 0.9478\text{ kJ/kg}\cdot\text{K} \end{array}$$




*Analysis* (*a*) The mass flow rate of air is

$$\dot{m}_{air} = \frac{P_3\dot{V}_3}{RT_3} = \frac{(100\text{ kPa})(6\text{ m}^3/\text{min})}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})} = 6.97\text{ kg/min}$$

We take the entire heat exchanger 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* (*for each fluid stream*):

$$\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system}^{\,\nearrow 0\text{ (steady)}} = 0 \quad \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_{air} \quad \text{and} \quad \dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

*Energy balance* (for the entire heat exchanger):

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

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

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} = \dot{W} = \Delta ke \approx \Delta pe \approx 0)$$

Combining the two, $\dot{m}_R(h_2 - h_1) = \dot{m}_{air}(h_3 - h_4) = \dot{m}_{air}c_p(T_3 - T_4)$

Solving for $T_4$, $T_4 = T_3 - \dfrac{\dot{m}_R(h_2 - h_1)}{\dot{m}_{air}c_p}$

Substituting, $T_4 = 27°\text{C} - \dfrac{(2\text{ kg/min})(236.97 - 86.83)\text{ kJ/kg}}{(6.97\text{ kg/min})(1.005\text{ kJ/kg}\cdot\text{K})} = \mathbf{-15.9°C} = 257.1\text{ K}$

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

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

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

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

or,

**7–199** A 4-m × 5-m × 7-m well-sealed room is to be heated by 1500 kg of liquid water contained in a tank that is placed in the room. The room is losing heat to the outside air at 5°C at an average rate of 10,000 kJ/h. The room is initially at 20°C and 100 kPa and is maintained at a temperature of 20°C at all times. If the hot water is to meet the heating requirements of this room for a 24-h period, determine (*a*) the minimum temperature of the water when it is first brought into the room and (*b*) the entropy generated during a 24-h period. Assume constant specific heats for both air and water at room temperature.

**7-199** A room is to be heated by hot water contained in a tank placed in the room. The minimum initial temperature of the water needed to meet the heating requirements of this room for a 24-h period and the entropy generated are to be determined.

***Assumptions*** 1 Water is an incompressible substance with constant specific heats. 2 Air is an ideal gas with constant specific heats. 3 The energy stored in the container itself is negligible relative to the energy stored in water. 4 The room is maintained at 20°C at all times. 5 The hot water is to meet the heating requirements of this room for a 24-h period.

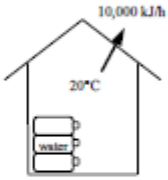
***Properties*** The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3).

***Analysis*** Heat loss from the room during a 24-h period is

$$Q_{loss} = (10{,}000 \text{ kJ/h})(24 \text{ h}) = 240{,}000 \text{ kJ}$$

Taking the contents of the room, including the water, as our system, the energy balance can be written as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}} \rightarrow -Q_{out} = \Delta U = (\Delta U)_{water} + (\Delta U)_{air}^{\nearrow 0}$$




or

$$-Q_{out} = [mc(T_2 - T_1)]_{water}$$

Substituting,

$$-240{,}000 \text{ kJ} = (1500 \text{ kg})(4.18 \text{ kJ/kg·°C})(20 - T_1)$$

It gives

$$T_1 = \mathbf{58.3°C}$$

where $T_1$ is the temperature of the water when it is first brought into the room.

(*b*) We take the house as the system, which is a closed system. The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the house 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 the extended system can be expressed as

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

$$-\frac{Q_{out}}{T_{b,out}} + S_{gen} = \Delta S_{water} + \Delta S_{air}^{\nearrow 0} = \Delta S_{water}$$

since the state of air in the house (and thus its entropy) remains unchanged. Then the entropy generated during the 24 h period becomes

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

$$= (1500 \text{ kg})(4.18 \text{ kJ/kg·K}) \ln \frac{293 \text{ K}}{331.3 \text{ K}} + \frac{240{,}000 \text{ kJ}}{278 \text{ K}}$$

$$= -770.3 + 863.3 = \mathbf{93.0 \text{ kJ/K}}$$

**7–207** (*a*) Water flows through a shower head steadily at a rate of 10 L/min. An electric resistance heater placed in the water pipe heats the water from 16 to 43°C. Taking the density of water to be 1 kg/L, determine the electric power input to the heater, in kW, and the rate of entropy generation during this process, in kW/K.

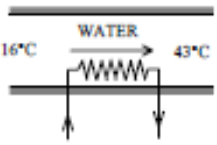
7-207 Water is heated from 16°C to 43°C by an electric resistance heater placed in the water pipe as it flows through a showerhead steadily at a rate of 10 L/min. The electric power input to the heater and the rate of entropy generation are to be determined. The reduction in power input and entropy generation as a result of installing a 50% efficient regenerator are also to be determined.

***Assumptions*** 1 This is a steady-flow process since there is no change with time at any point within the system and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$. 2 Water is an incompressible substance with constant specific heats. 3 The kinetic and potential energy changes are negligible, $\Delta ke \approx \Delta pe \approx 0$. 4 Heat losses from the pipe are negligible.

***Properties*** The density of water is given to be $\rho = 1$ kg/L. The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3).

***Analysis*** (*a*) We take the pipe as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Then the energy balance for this steady-flow system can be expressed in the rate form as

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




$$\dot{W}_{e,in} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \Delta ke \approx \Delta pe \approx 0)$$

$$\dot{W}_{e,in} = \dot{m}(h_2 - h_1) = \dot{m}c(T_2 - T_1)$$

where $\dot{m} = \rho\dot{V} = (1\ \text{kg/L})(10\ \text{L/min}) = 10\ \text{kg/min}$

Substituting, $\dot{W}_{e,in} = (10/60\ \text{kg/s})(4.18\ \text{kJ/kg}\cdot{}^\circ\text{C})(43-16)^\circ\text{C} = \mathbf{18.8\ kW}$

The rate of entropy generation in the heating section during this process is determined by applying the entropy balance on the heating section. Noting that this is a steady-flow process and heat transfer from the heating section is negligible,

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

$$\dot{m}s_1 - \dot{m}s_2 + \dot{S}_{gen} = 0 \longrightarrow \dot{S}_{gen} = \dot{m}(s_2 - s_1)$$

Noting that water is an incompressible substance and substituting,

$$\dot{S}_{gen} = \dot{m}c\ln\frac{T_2}{T_1} = (10/60\ \text{kg/s})(4.18\ \text{kJ/kg}\cdot\text{K})\ln\frac{316\ \text{K}}{289\ \text{K}} = \mathbf{0.0622\ kJ/K}$$

(*b*) The energy recovered by the heat exchanger is

$$\dot{Q}_{saved} = \varepsilon\dot{Q}_{max} = \varepsilon\dot{m}C(T_{max} - T_{min}) = 0.5(10/60\ \text{kg/s})(4.18\ \text{kJ/kg}\cdot{}^\circ\text{C})(39-16)^\circ\text{C} = 8.0\ \text{kJ/s} = 8.0\ \text{kW}$$

Therefore, 8.0 kW less energy is needed in this case, and the required electric power in this case reduces to

$$\dot{W}_{in,new} = \dot{W}_{in,old} - \dot{Q}_{saved} = 18.8 - 8.0 = \mathbf{10.8\ kW}$$

Taking the cold water stream in the heat exchanger as our control volume (a steady-flow system), the temperature at which the cold water leaves the heat exchanger and enters the electric resistance heating section is determined from

$$\dot{Q} = \dot{m}c(T_{c,out} - T_{c,in})$$

Substituting, $8\ \text{kJ/s} = (10/60\ \text{kg/s})(4.18\ \text{kJ/kg}\cdot{}^\circ\text{C})(T_{c,out} - 16^\circ\text{C})$

It yields $T_{c,out} = 27.5^\circ\text{C} = 300.5\text{K}$

The rate of entropy generation in the heating section in this case is determined similarly to be

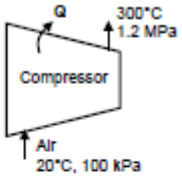
$$\dot{S}_{gen} = \dot{m}c\ln\frac{T_2}{T_1} = (10/60\ \text{kg/s})(4.18\ \text{kJ/kg}\cdot\text{K})\ln\frac{316\ \text{K}}{300.5\ \text{K}} = \mathbf{0.0350\ kJ/K}$$

Thus the reduction in the rate of entropy generation within the heating section is

$$\dot{S}_{reduction} = 0.0622 - 0.0350 = \mathbf{0.0272\ kW/K}$$

**7–211** Air is compressed steadily by a compressor from 100 kPa and 20°C to 1200 kPa and 300°C at a rate of 0.4 kg/s. The compressor is intentionally cooled by utilizing fins on the surface of the compressor and heat is lost from the compressor at a rate of 15 kW to the surroundings at 20°C. Using constant specific heats at room temperature, determine (*a*) the power input to the compressor, (*b*) the isothermal efficiency, and (*c*) the entropy generation during this process.

**7-211** Air is compressed in a compressor that is intentionally cooled. The work input, the isothermal efficiency, and the entropy generation are to be determined.




***Assumptions*** 1 Steady operating conditions exist. 2 Kinetic and potential energy changes are 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 an average temperature of (20+300)/2 = 160°C = 433 K is $c_p$ = 1.018 kJ/kg.K (Table A-2).

***Analysis*** (*a*) The power input is determined from an energy balance on the control volume

$$\dot{W}_C = \dot{m}c_p(T_2 - T_1) + \dot{Q}_{out}$$
$$= (0.4\,\text{kg/s})(1.018\,\text{kJ/kg.°C})(300-20)\text{°C} + 15\,\text{kW}$$
$$= \mathbf{129.0\,kW}$$

(*b*) The power input for a reversible-isothermal process is given by

$$\dot{W}_{T=\text{const.}} = \dot{m}RT_1 \ln\frac{P_2}{P_1} = (0.4\,\text{kg/s})(0.287\,\text{kJ/kg.K})(20+273\,\text{K})\ln\left(\frac{1200\,\text{kPa}}{100\,\text{kPa}}\right) = 83.6\,\text{kW}$$

Then, the isothermal efficiency of the compressor becomes

$$\eta_T = \frac{\dot{W}_{T=\text{const.}}}{\dot{W}_C} = \frac{83.6\,\text{kW}}{129.0\,\text{kW}} = \mathbf{0.648}$$

(*c*) The rate of entropy generation associated with this process may be obtained by adding the rate of entropy change of air as it flows in the compressor and the rate of entropy change of the surroundings

$$\dot{S}_{gen} = \Delta\dot{S}_{air} + \Delta\dot{S}_{surr} = c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1} + \frac{\dot{Q}_{out}}{T_{surr}}$$
$$= (1.018\,\text{kJ/kg.K})\ln\frac{300+273\,\text{K}}{20+273\,\text{K}} - (0.287\,\text{kJ/kg.K})\ln\frac{1200\,\text{kPa}}{100\,\text{kPa}} + \frac{15\,\text{kW}}{(20+273)\,\text{K}}$$
$$= \mathbf{0.0390\,kW/K}$$