Thermo 1 (MEP 261)

Thermodynamics An Engineering Approach

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Sheet 7:Chapter 7

7–25 Air is compressed by a 12-kW compressor from P_1 to P_2. The air temperature is maintained constant at 25°C during this process as a result of heat transfer to the surrounding medium at 10°C. Determine the rate of entropy change of the air. State the assumptions made in solving this problem.
Answer: - 0.0403 kW/K

Solution Air is compressed steadily by a compressor. The air temperature is maintained constant by heat rejection to the surroundings. The rate of entropy change of air 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** Air is an ideal gas. **4** The process involves no internal irreversibilities such as friction, and thus it is an isothermal, internally reversible process.

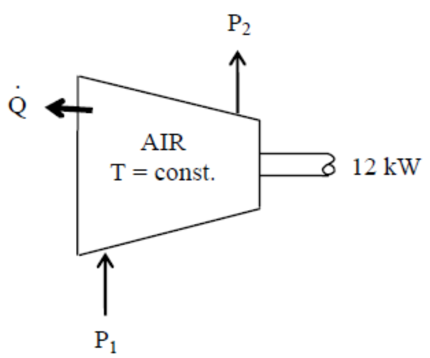
Properties Noting that $h = h(T)$ for ideal gases, we have $h_1 = h_2$ since $T_1 = T_2 = 25°C$.

Analysis We take the compressor as the system. Noting that the enthalpy of air remains constant, the energy balance for this steady-flow system can be expressed in the rate form as

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

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

$$\dot{W}_{in} = \dot{Q}_{out}$$



Therefore,

$$\dot{Q}_{out} = \dot{W}_{in} = 12\text{ kW}$$

Noting that the process is assumed to be an isothermal and internally reversible process, the rate of entropy change of air is determined to be

$$\Delta \dot{S}_{air} = -\frac{\dot{Q}_{out,air}}{T_{sys}} = -\frac{12\text{ kW}}{298\text{ K}} = \mathbf{-0.0403\ kW/K}$$

7–26 During the isothermal heat addition process of a Carnot cycle, 900 kJ of heat is added to the working fluid from a source at 400°C. Determine (*a*) the entropy change of the working fluid, (*b*) the entropy change of the source, and (*c*) the total entropy change for the process.

Solution Heat is transferred isothermally from a source to the working fluid of a Carnot engine. The entropy change of the working fluid, the entropy change of the source, and the total entropy change during this process are to be determined.

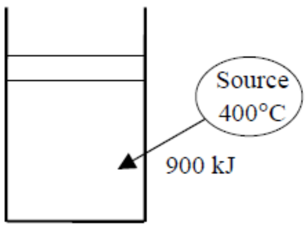
Analysis (*a*) This is a reversible isothermal process, and the entropy change during such a process is given by

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

Noting that heat transferred from the source is equal to the heat transferred to the working fluid, the entropy changes of the fluid and of the source become

$$\Delta S_{\text{fluid}} = \frac{Q_{\text{fluid}}}{T_{\text{fluid}}} = \frac{Q_{\text{in,fluid}}}{T_{\text{fluid}}} = \frac{900 \text{ kJ}}{673 \text{ K}} = \mathbf{1.337 \text{ kJ/K}}$$

(*b*)
$$\Delta S_{\text{source}} = \frac{Q_{\text{source}}}{T_{\text{source}}} = -\frac{Q_{\text{out, source}}}{T_{\text{source}}} = -\frac{900 \text{ kJ}}{673 \text{ K}} = \mathbf{-1.337 \text{ kJ/K}}$$



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

$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{fluid}} + \Delta S_{\text{source}} = 1.337 - 1.337 = \mathbf{0}$$

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.

Solution 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.

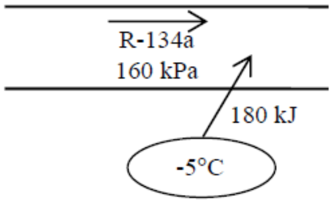
Assumptions **1** Both the refrigerant and the cooled space involve no internal irreversibilities such as friction. **2** Any temperature change occurs within the wall of the tube, and thus both the refrigerant and the cooled space remain isothermal during this process. Thus it is an isothermal, internally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

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

(*b*) Similarly,

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

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

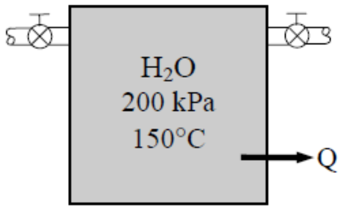
$$S_{\text{gen}} = S_{\text{total}} = \Delta S_{\text{refrigerant}} + \Delta S_{\text{space}} = 0.699 - 0.672 = \mathbf{0.027 \text{ kJ/K}}$$

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

Solution 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),

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



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

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

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

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

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

Solution 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)

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

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

The mass of the refrigerant is

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

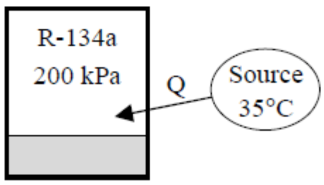
Then the entropy change of the refrigerant becomes

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

(*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

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

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

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

7–34 A well-insulated rigid tank contains 2 kg of a saturated liquid–vapor mixture of water at 100 kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistance heater placed in the tank is now turned on and kept on until all the liquid in the tank is vaporized. Determine the entropy change of the steam during this process. *Answer:* 8.10 kJ/K

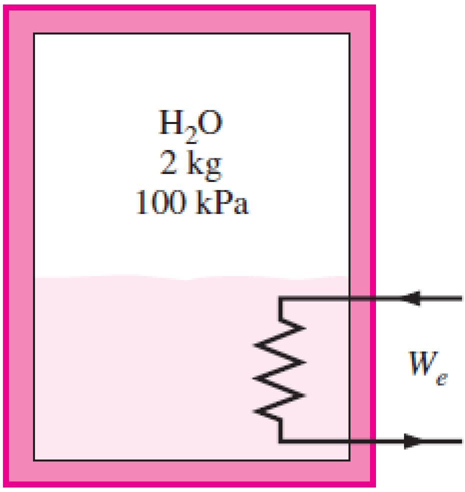


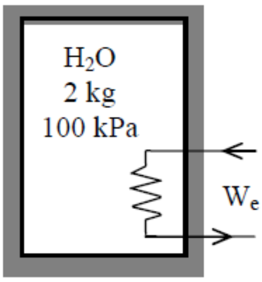
FIGURE P7–34

Solution An insulated rigid tank contains a saturated liquid-vapor mixture of water at a specified pressure. An electric heater inside is turned on and kept on until all the liquid vaporized. The entropy change of the water during this process is to be determined.

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

$$\left.\begin{array}{l} P_1 = 100 \text{ kPa} \\ x_1 = 0.25 \end{array}\right\} \begin{array}{l} v_1 = v_f + x_1 v_{fg} = 0.001 + (0.25)(1.6941 - 0.001) = 0.4243 \text{ m}^3/\text{kg} \\ s_1 = s_f + x_1 s_{fg} = 1.3028 + (0.25)(6.0562) = 2.8168 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left.\begin{array}{l} v_2 = v_1 \\ \text{sat. vapor} \end{array}\right\} s_2 = 6.8649 \text{ kJ/kg} \cdot \text{K}$$



Then the entropy change of the steam becomes

$$\Delta S = m(s_2 - s_1) = (2 \text{ kg})(6.8649 - 2.8168) \text{ kJ/kg} \cdot \text{K} = \mathbf{8.10 \ \ kJ/K}$$

7–35 A rigid tank is divided into two equal parts by a partition. One part of the tank contains 1.5 kg of compressed liquid water at 300 kPa and 60°C while the other part is evacuated. The partition is now removed, and the water expands to fill the entire tank. Determine the entropy change of water during this process, if the final pressure in the tank is 15 kPa. *Answer:* −0.114 kJ/K

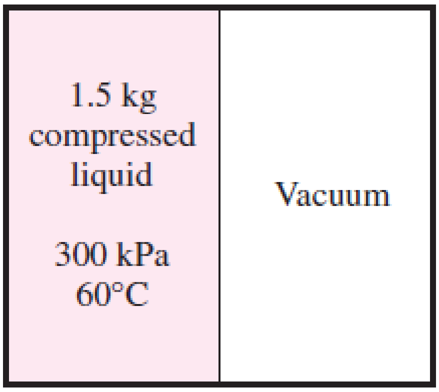
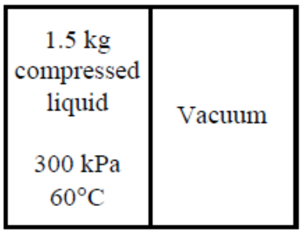


FIGURE P7–35

Solution A rigid tank is divided into two equal parts by a partition. One part is filled with compressed liquid water while the other side is evacuated. The partition is removed and water expands into the entire tank. The entropy change of the water during this process is to be determined.

Analysis The properties of the water are (Table A-4)

$$\left.\begin{array}{l} P_1 = 300 \text{ kPa} \\ T_1 = 60°\text{C} \end{array}\right\} \begin{array}{l} v_1 \cong v_{f@60°\text{C}} = 0.001017 \text{m}^3/\text{kg} \\ s_1 = s_{f@60°\text{C}} = 0.8313 \text{ kJ/kg}\cdot\text{K} \end{array}$$



Noting that $v_2 = 2v_1 = (2)(0.001017) = 0.002034 \text{ m}^3/\text{kg}$

$$\left.\begin{array}{l} P_2 = 15 \text{ kPa} \\ v_2 = 0.002034 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{l} x_2 = \dfrac{v_2 - v_f}{v_{fg}} = \dfrac{0.002034 - 0.001014}{10.02 - 0.001014} = 0.0001018 \\ s_2 = s_f + x_2 s_{fg} = 0.7549 + (0.0001018)(7.2522) = 0.7556 \text{ kJ/kg}\cdot\text{K} \end{array}$$

Then the entropy change of the water becomes

$$\Delta S = m(s_2 - s_1) = (1.5 \text{ kg})(0.7556 - 0.8313) \text{kJ/kg}\cdot\text{K} = \mathbf{-0.114 \text{ kJ/K}}$$

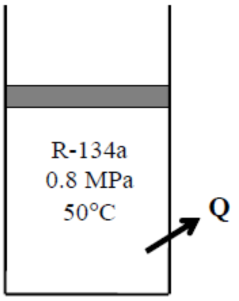
7–38 A cylinder is initially filled with refrigerant R-134a vapor at 50°C and 0.8-MPa. The refrigerant is now cooled and condensed at constant pressure until the temperature drops to 20°C. Determine the entropy change of the refrigerant during this process.

Solution A cylinder is initially filled with R-134a at a specified state. The refrigerant is cooled and condensed at constant pressure. The entropy change of refrigerant during this process is to be determined

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

$$\left.\begin{array}{l} P_1 = 0.8 \text{ MPa} \\ T_1 = 50°\text{C} \end{array}\right\} s_1 = 0.98021 \text{ kJ/kg} \cdot \text{K}$$

$$\left.\begin{array}{l} T_2 = 20°\text{C} \\ P_2 = 0.8 \text{ MPa} \end{array}\right\} s_2 \cong s_{f@20°\text{C}} = 0.30063 \text{ kJ/kg} \cdot \text{K}$$



Then the entropy change of the refrigerant becomes

$$\Delta S = m(s_2 - s_1) = (1 \text{ kg})(0.30063 - 0.98021)\text{kJ/kg} \cdot \text{K} = \mathbf{-0.6796 \ kJ/K}$$

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.

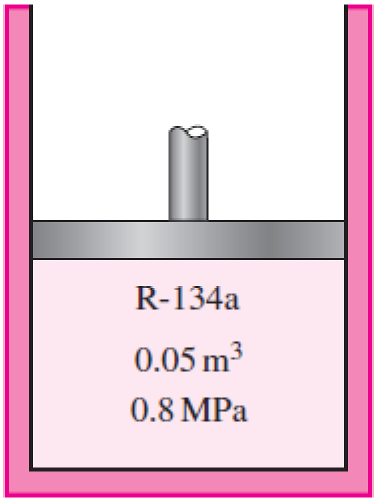


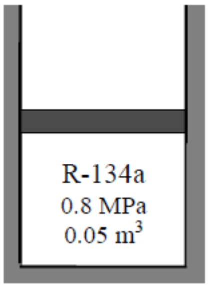
FIGURE P7–39

Solution 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

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

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

(*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 m^3/min and is compressed to a pressure of 900 kPa. Determine the minimum power that must be supplied to the compressor.

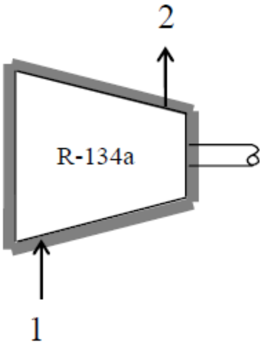
Solution Saturated refrigerant-134a vapor at 160 kPa is compressed steadily by an adiabatic compressor. The minimum power input to the compressor is to be determined.

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

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

7–42 Steam enters an adiabatic turbine at 6 MPa and 500° C and leaves at a pressure of 300 kPa. Determine the maximum amount of work that can be delivered by this turbine.

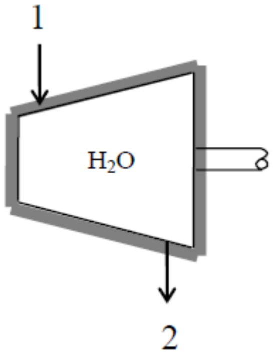
Solution Steam expands in an adiabatic turbine. The maximum amount of work that can be done by the turbine is to be determined.

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 device is adiabatic and thus heat transfer is negligible.

Analysis The work output of an adiabatic turbine is a maximum when the expansion process is reversible. For the reversible adiabatic process we have $s_2 = s_1$. From the steam tables (Tables A-4 through A-6),

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

$$\left.\begin{array}{l} P_2 = 300 \text{ kPa} \\ s_2 = s_1 \end{array}\right\} \begin{array}{l} x_2 = \dfrac{s_2 - s_f}{s_{fg}} = \dfrac{6.8826 - 1.6717}{5.3200} = 0.9795 \\ h_2 = h_f + x_2 h_{fg} = 561.43 + (0.9795)(2163.5) = 2680.6 \text{ kJ/kg} \end{array}$$



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

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

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

$$\dot{m}h_1 = \dot{W}_{out} + \dot{m}h_2$$

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

Dividing by mass flow rate and substituting,

$$w_{out} = h_1 - h_2 = 3423.1 - 2680.6 = \mathbf{742.6 \text{ kJ/kg}}$$

7–44 A heavily insulated piston–cylinder device contains 0.05 m^3 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.

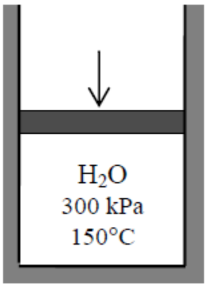
Solution An insulated cylinder is initially filled with superheated steam at a specified state. The steam is compressed in a reversible manner until the pressure drops to a specified value. The work input during this process is to be determined.

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

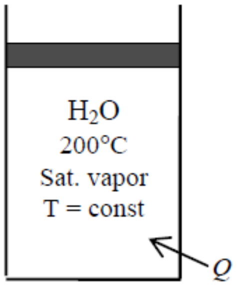
$$W_{b,in} = m(u_2 - u_1) = (0.0789\text{ kg})(2773.8 - 2571.0)\text{ kJ/kg} = \mathbf{16.0\ kJ}$$

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.

Solution 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.

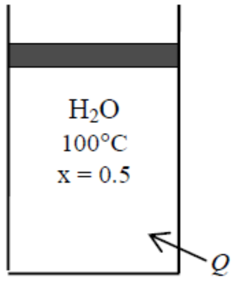
(*b*) Determine the heat added to the steam in process 1-2, in kJ.

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

Solution 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)



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

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

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

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

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

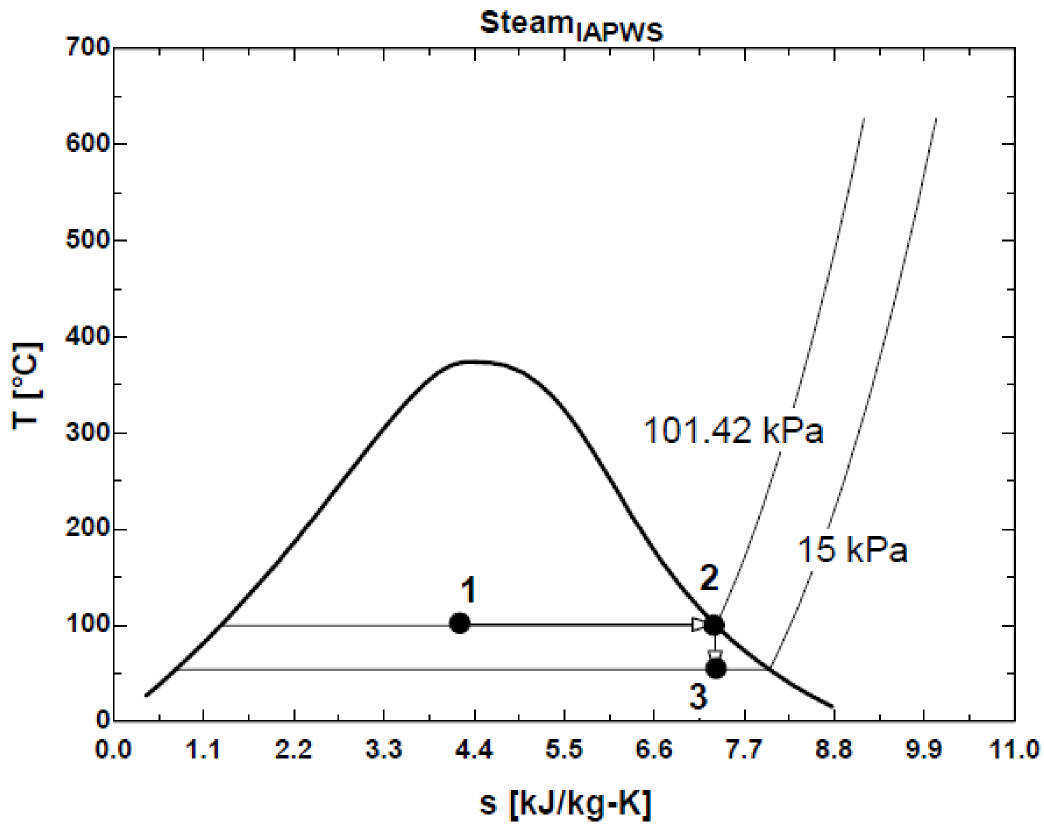
$$Q_{\text{in}} - W_{\text{b,out}} = \Delta U = m(u_2 - u_1)$$

For process 1–2, it reduces to

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

(c) For process 2–3, it reduces to

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



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.

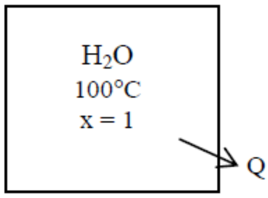
(*c*) For the steam and its surroundings, determine the total entropy change or S_{gen} associated with this process, in kJ/K.

Solution 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)

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



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

The entropy change of steam is determined from

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

(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

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

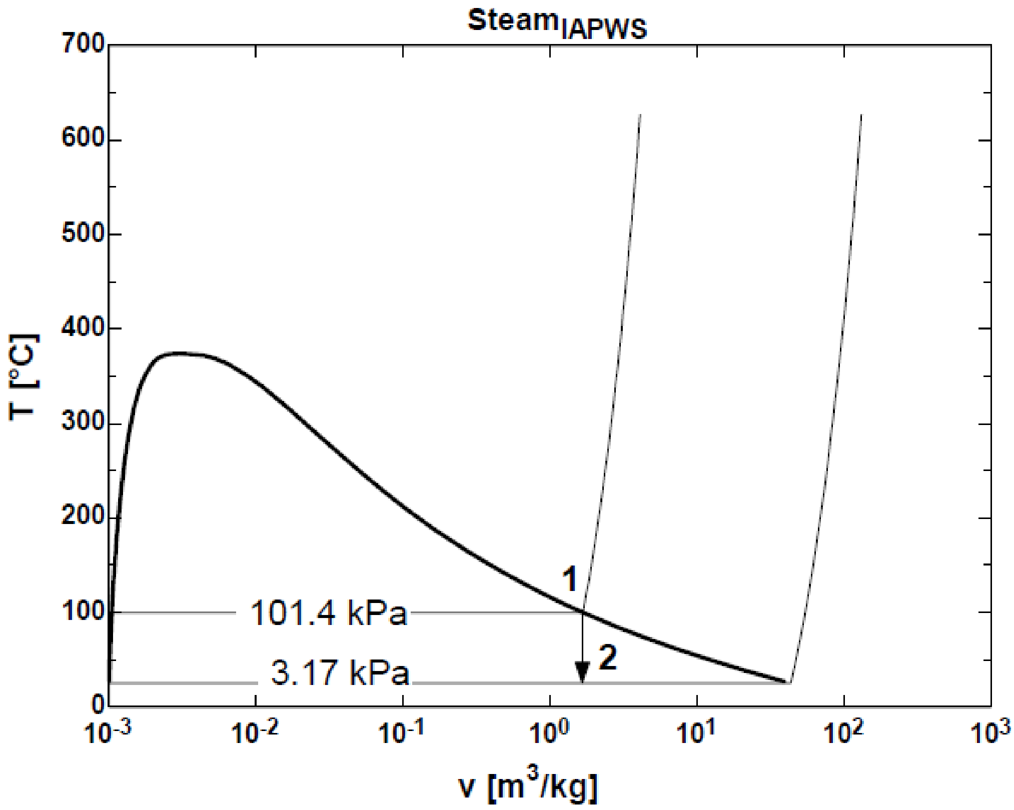
$$-Q_{out} = \Delta U = m(u_2 - u_1)$$

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

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



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.

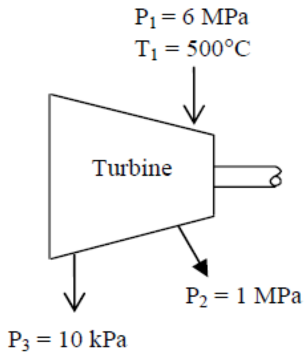
(*a*) Sketch the process on a *T*-*s* diagram with respect to the saturation lines. Be sure to label the data states and the lines of constant pressure.

(*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?

Solution 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 is 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)



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

$$\left.\begin{array}{l} P_2 = 1\,\text{MPa} \\ s_2 = s_1 \end{array}\right\} h_{2s} = 2921.3\text{ kJ/kg}$$

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

A mass balance on the control volume gives

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$$

where

$$\dot{m}_2 = 0.1\dot{m}_1$$
$$\dot{m}_3 = 0.9\dot{m}_1$$

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

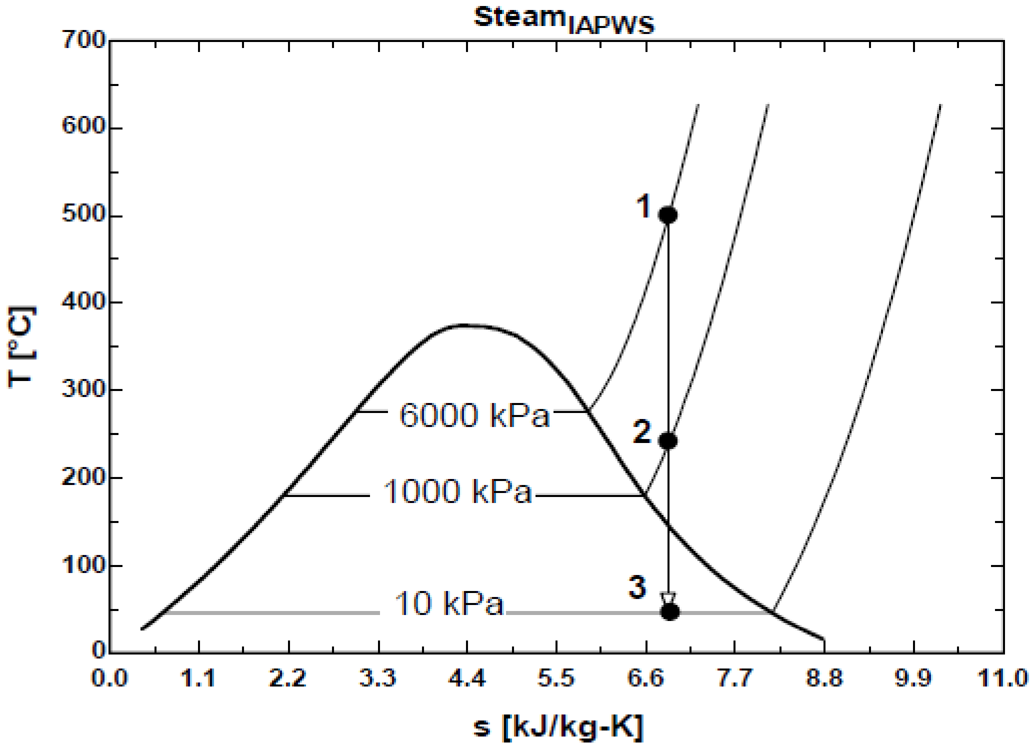
$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$
$$\dot{m}_1 h_1 = \dot{W}_{s,\text{out}} + \dot{m}_2 h_2 + \dot{m}_3 h_3$$
$$\dot{m}_1 h_1 = \dot{W}_{s,\text{out}} + 0.1\dot{m}_1 h_2 + 0.9\dot{m}_1 h_3$$

or

$$h_1 = w_{s,\text{out}} + 0.1h_2 + 0.9h_3$$
$$w_{s,\text{out}} = h_1 - 0.1h_2 - 0.9h_3$$
$$= 3423.1 - (0.1)(2921.3) - (0.9)(2179.6) = 1169.3\,\text{kJ/kg}$$

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

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



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.

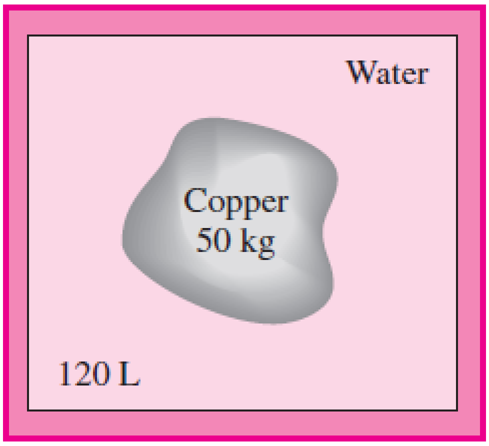


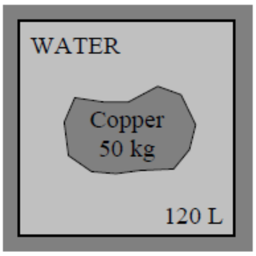
FIGURE P7–53

Solution 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,

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

$$T_2 = \mathbf{27.0°C}$$

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.

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

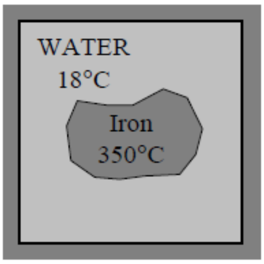
Assumptions **1** Both the water and the iron block are incompressible substances with constant specific heats at room temperature. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The tank is well insulated and thus there is no heat transfer. **4** The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

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

$$T_2 = \mathbf{26.7^\circ C}$$

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

Solution 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.

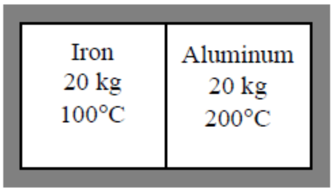
Assumptions **1** Both the aluminum and the iron block are incompressible substances with constant specific heats. **2** The system is stationary and thus the kinetic and potential energies are negligible. **3** The system is well insulated and thus there is no heat transfer.

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 and 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,

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

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

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,

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