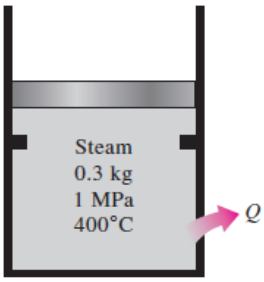
Energy Analysis of Closed Systems Study Questions

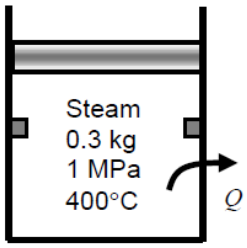
4–6 A piston–cylinder device with a set of stops initially contains 0.3 kg of steam at 1.0 MPa and 400°C. The location of the stops corresponds to 60 percent of the initial volume. Now the steam is cooled. Determine the compression work if the final state is (*a*) 1.0 MPa and 250°C and (*b*) 500 kPa. (*c*) Also determine the temperature at the final state in part (*b*).



4-6 A piston-cylinder device with a set of stops contains steam at a specified state. Now, the steam is cooled. The compression work for two cases and the final temperature are to be determined.

Analysis (a) The specific volumes for the initial and final states are (Table A-6)

$$\left.\begin{array}{l} P_1 = 1\,\text{MPa} \\ T_1 = 400°\text{C} \end{array}\right\} v_1 = 0.30661\,\text{m}^3/\text{kg} \qquad \left.\begin{array}{l} P_2 = 1\,\text{MPa} \\ T_2 = 250°\text{C} \end{array}\right\} v_2 = 0.23275\,\text{m}^3/\text{kg}$$



Noting that pressure is constant during the process, the boundary work is determined from

$$W_b = mP(v_1 - v_2) = (0.3\,\text{kg})(1000\,\text{kPa})(0.30661 - 0.23275)\text{m}^3/\text{kg} = \mathbf{22.16\ kJ}$$

(b) The volume of the cylinder at the final state is 60% of initial volume. Then, the boundary work becomes

$$W_b = mP(v_1 - 0.60v_1) = (0.3\,\text{kg})(1000\,\text{kPa})(0.30661 - 0.60 \times 0.30661)\text{m}^3/\text{kg} = \mathbf{36.79\ kJ}$$

The temperature at the final state is

$$\left.\begin{array}{l} P_2 = 0.5\,\text{MPa} \\ v_2 = (0.60 \times 0.30661)\,\text{m}^3/\text{kg} \end{array}\right\} T_2 = \mathbf{151.8°C} \quad \text{(Table A-5)}$$

4–8 A mass of 5 kg of saturated water vapor at 300 kPa is heated at constant pressure until the temperature reaches 200°C. Calculate the work done by the steam during this process. *Answer:* 165.9 kJ

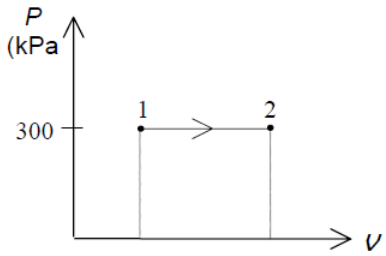
4-8 Saturated water vapor in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Properties Noting that the pressure remains constant during this process, the specific volumes at the initial and the final states are (Table A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 300 \text{ kPa} \\ \text{Sat. vapor} \end{array}\right\} v_1 = v_{g@300\text{ kPa}} = 0.60582 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 300 \text{ kPa} \\ T_2 = 200°\text{C} \end{array}\right\} v_2 = 0.71643 \text{ m}^3/\text{kg}$$



Analysis The boundary work is determined from its definition to be

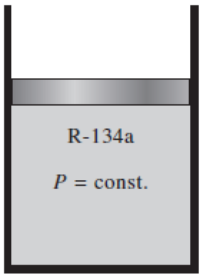
$$W_{b,\text{out}} = \int_1^2 P\,dV = P(V_2 - V_1) = mP(v_2 - v_1)$$

$$= (5 \text{ kg})(300 \text{ kPa})(0.71643 - 0.60582) \text{ m}^3/\text{kg}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{165.9\ kJ}$$

Discussion The positive sign indicates that work is done by the system (work output).

4–9 A frictionless piston–cylinder device initially contains 200 L of saturated liquid refrigerant-134a. The piston is free to move, and its mass is such that it maintains a pressure of 900 kPa on the refrigerant. The refrigerant is now heated until its temperature rises to 70°C. Calculate the work done during this process. *Answer:* 5571 kJ



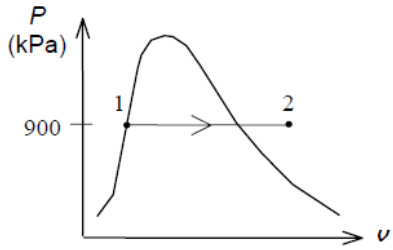
4-9 Refrigerant-134a in a cylinder is heated at constant pressure until its temperature rises to a specified value. The boundary work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Properties Noting that the pressure remains constant during this process, the specific volumes at the initial and the final states are (Table A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 900 \text{ kPa} \\ \text{Sat. liquid} \end{array}\right\} v_1 = v_{f\,@\,900\text{ kPa}} = 0.0008580 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 900 \text{ kPa} \\ T_2 = 70°\text{C} \end{array}\right\} v_2 = 0.027413 \text{ m}^3/\text{kg}$$



Analysis The boundary work is determined from its definition to be

$$m = \frac{V_1}{v_1} = \frac{0.2 \text{ m}^3}{0.0008580 \text{ m}^3/\text{kg}} = 233.1 \text{ kg}$$

and

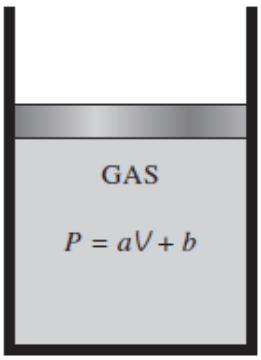
$$W_{b,\text{out}} = \int_1^2 P\,dV = P(V_2 - V_1) = mP(v_2 - v_1)$$

$$= (233.1 \text{ kg})(900 \text{ kPa})(0.027413 - 0.0008580)\text{m}^3/\text{kg}\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right)$$

$$= \mathbf{5571\ kJ}$$

Discussion The positive sign indicates that work is done by the system (work output).

4–14 A gas is compressed from an initial volume of 0.42 m^3 to a final volume of 0.12 m^3. During the quasi-equilibrium process, the pressure changes with volume according to the relation $P = aV + b$, where $a = -1200$ kPa/m^3 and $b = 600$ kPa. Calculate the work done during this process (*a*) by plotting the process on a P-V diagram and finding the area under the process curve and (*b*) by performing the necessary integrations.



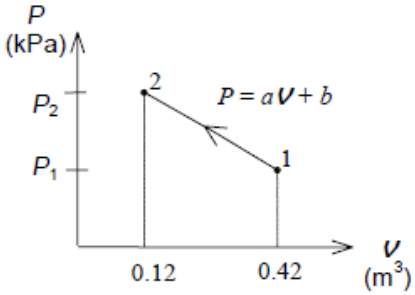
4-14 A gas in a cylinder is compressed to a specified volume in a process during which the pressure changes linearly with volume. The boundary work done during this process is to be determined by plotting the process on a P-V diagram and also by integration.

Assumptions The process is quasi-equilibrium.

Analysis (*a*) The pressure of the gas changes linearly with volume, and thus the process curve on a P-V diagram will be a straight line. The boundary work during this process is simply the area under the process curve, which is a trapezoidal. Thus,

$$P_1 = aV_1 + b = (-1200\ \text{kPa/m}^3)(0.42\ \text{m}^3) + (600\ \text{kPa}) = 96\ \text{kPa}$$

$$P_2 = aV_2 + b = (-1200\ \text{kPa/m}^3)(0.12\ \text{m}^3) + (600\ \text{kPa}) = 456\ \text{kPa}$$



and

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1)$$

$$= \frac{(96 + 456)\text{kPa}}{2}(0.12 - 0.42)\text{m}^3\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

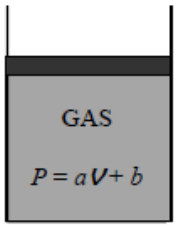
$$= \mathbf{-82.8\ kJ}$$

(*b*) The boundary work can also be determined by integration to be

$$W_{b,\text{out}} = \int_1^2 P\,dV = \int_1^2 (aV + b)\,dV = a\frac{V_2^2 - V_1^2}{2} + b(V_2 - V_1)$$

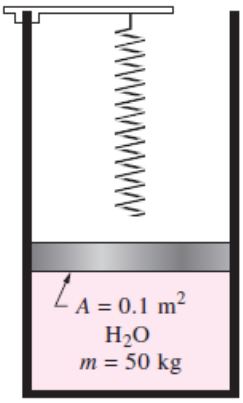
$$= (-1200\ \text{kPa/m}^3)\frac{(0.12^2 - 0.42^2)\text{m}^6}{2} + (600\ \text{kPa})(0.12 - 0.42)\text{m}^3$$

$$= \mathbf{-82.8\ kJ}$$



Discussion The negative sign indicates that work is done on the system (work input).

4–23 A piston–cylinder device contains 50 kg of water at 250 kPa and 25°C. The cross-sectional area of the piston is 0.1 m^2. Heat is now transferred to the water, causing part of it to evaporate and expand. When the volume reaches 0.2 m^3, the piston reaches a linear spring whose spring constant is 100 kN/m. More heat is transferred to the water until the piston rises 20 cm more. Determine (*a*) the final pressure and temperature and (*b*) the work done during this process. Also, show the process on a *P-V* diagram. *Answers:* (*a*) 450 kPa, 147.9°C, (*b*) 44.5 kJ



4-23 Water in a cylinder equipped with a spring is heated and evaporated. The vapor expands until it compresses the spring 20 cm. The final pressure and temperature, and the boundary work done are to be determined, and the process is to be shown on a *P-V* diagram.

Assumptions The process is quasi-equilibrium.

Analysis (*a*) The final pressure is determined from

$$P_3 = P_2 + \frac{F_s}{A} = P_2 + \frac{kx}{A} = (250\text{ kPa}) + \frac{(100\text{ kN/m})(0.2\text{ m})}{0.1\text{ m}^2}\left(\frac{1\text{ kPa}}{1\text{ kN/m}^2}\right) = \mathbf{450\ kPa}$$

The specific and total volumes at the three states are

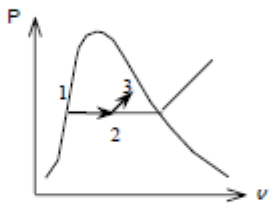
$$\left.\begin{array}{l} T_1 = 25°\text{C} \\ P_1 = 250\text{ kPa} \end{array}\right\} v_1 \cong v_{f\,@\,25°\text{C}} = 0.001003\text{ m}^3/\text{kg}$$

$$V_1 = mv_1 = (50\text{ kg})(0.001003\text{ m}^3/\text{kg}) = 0.05\text{ m}^3$$

$$V_2 = 0.2\text{ m}^3$$

$$V_3 = V_2 + x_{23}A_p = (0.2\text{ m}^3) + (0.2\text{ m})(0.1\text{ m}^2) = 0.22\text{ m}^3$$

$$v_3 = \frac{V_3}{m} = \frac{0.22\text{ m}^3}{50\text{ kg}} = 0.0044\text{ m}^3/\text{kg}$$



At 450 kPa, $v_f = 0.001088$ m^3/kg and $v_g = 0.41392$ m^3/kg. Noting that $v_f < v_3 < v_g$, the final state is a saturated mixture and thus the final temperature is

$$T_3 = T_{\text{sat@450 kPa}} = \mathbf{147.9°C}$$

(*b*) The pressure remains constant during process 1-2 and changes linearly (a straight line) during process 2-3. Then the boundary work during this process is simply the total area under the process curve,

$$W_{b,\text{out}} = \text{Area} = P_1(V_2 - V_1) + \frac{P_2 + P_3}{2}(V_3 - V_2)$$

$$= \left((250\text{ kPa})(0.2 - 0.05)\text{m}^3 + \frac{(250 + 450)\text{ kPa}}{2}(0.22 - 0.2)\text{m}^3\right)\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

$$= \mathbf{44.5\ kJ}$$

Discussion The positive sign indicates that work is done by the system (work output).

4–28 A 0.5-m³ rigid tank contains refrigerant-134a initially at 160 kPa and 40 percent quality. Heat is now transferred to the refrigerant until the pressure reaches 700 kPa. Determine (*a*) the mass of the refrigerant in the tank and (*b*) the amount of heat transferred. Also, show the process on a *P*-*v* diagram with respect to saturation lines.

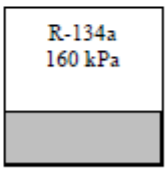
4-28 A rigid tank is initially filled with superheated R-134a. Heat is transferred to the tank until the pressure inside rises to a specified value. The mass of the refrigerant and the amount of heat transfer are to be determined, and the process is to be shown on a *P*-*v* diagram.

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

Analysis (*a*) 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

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

$$Q_{in} = \Delta U = m(u_2 - u_1) \quad (\text{since } W = \text{KE} = \text{PE} = 0)$$

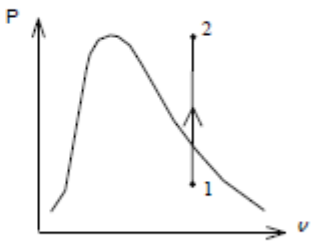


Using data from the refrigerant tables (Tables A-11 through A-13), the properties of R-134a are determined to be

$$\left.\begin{array}{l} P_1 = 160 \text{ kPa} \\ x_1 = 0.4 \end{array}\right\} \begin{array}{ll} v_f = 0.0007437, & v_g = 0.12348 \text{ m}^3/\text{kg} \\ u_f = 31.09, & u_{fg} = 190.27 \text{ kJ/kg} \end{array}$$

$$v_1 = v_f + x_1 v_{fg} = 0.0007437 + 0.4(0.12348 - 0.0007437) = 0.04984 \text{ m}^3/\text{kg}$$
$$u_1 = u_f + x_1 u_{fg} = 31.09 + 0.4(190.27) = 107.19 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 700 \text{ kPa} \\ (v_2 = v_1) \end{array}\right\} u_2 = 376.99 \text{ kJ/kg (Superheated vapor)}$$



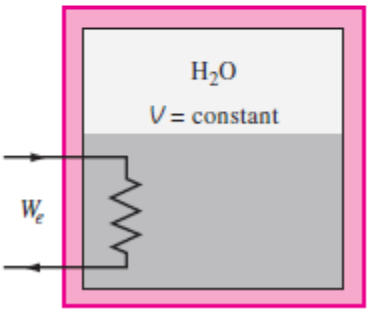
Then the mass of the refrigerant is determined to be

$$m = \frac{V_1}{v_1} = \frac{0.5 \text{ m}^3}{0.04984 \text{ m}^3/\text{kg}} = \mathbf{10.03 \text{ kg}}$$

(*b*) Then the heat transfer to the tank becomes

$$\begin{aligned} Q_{in} &= m(u_2 - u_1) \\ &= (10.03 \text{ kg})(376.99 - 107.19) \text{ kJ/kg} \\ &= \mathbf{2707 \text{ kJ}} \end{aligned}$$

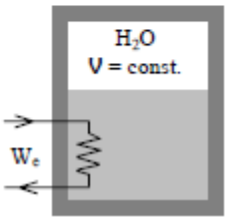
4–30 A well-insulated rigid tank contains 5 kg of a saturated liquid–vapor mixture of water at 100 kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistor placed in the tank is connected to a 110-V source, and a current of 8 A flows through the resistor when the switch is turned on. Determine how long it will take to vaporize all the liquid in the tank. Also, show the process on a T-v diagram with respect to saturation lines.



4-30 An insulated rigid tank is initially filled with a saturated liquid-vapor mixture of water. An electric heater in the tank is turned on, and the entire liquid in the tank is vaporized. The length of time the heater was kept on is to be determined, and the process is to be shown on a P-v diagram.

Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** The device is well-insulated and thus heat transfer is negligible. **3** The energy stored in the resistance wires, and the heat transferred to the tank itself is negligible.

Analysis We take the contents of 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



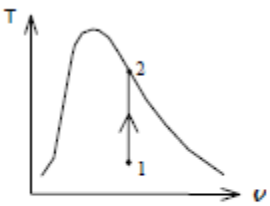
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

$$W_{e,in} = \Delta U = m(u_2 - u_1) \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$

$$VI\Delta t = m(u_2 - u_1)$$

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

$$\left.\begin{array}{l} P_1 = 100\text{kPa} \\ x_1 = 0.25 \end{array}\right\} \begin{array}{ll} v_f = 0.001043, & v_g = 1.6941\ \text{m}^3/\text{kg} \\ u_f = 417.40, & u_{fg} = 2088.2\ \text{kJ/kg} \end{array}$$



$$v_1 = v_f + x_1 v_{fg} = 0.001043 + [0.25 \times (1.6941 - 0.001043)] = 0.42431\ \text{m}^3/\text{kg}$$

$$u_1 = u_f + x_1 u_{fg} = 417.40 + (0.25 \times 2088.2) = 939.4\ \text{kJ/kg}$$

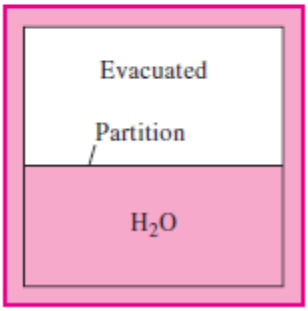
$$\left.\begin{array}{l} v_2 = v_1 = 0.42431\ \text{m}^3/\text{kg} \\ \text{sat.vapor} \end{array}\right\} u_2 = u_{g@0.42431\text{m}^3/\text{kg}} = 2556.2\ \text{kJ/kg}$$

Substituting,

$$(110\ \text{V})(8\ \text{A})\Delta t = (5\ \text{kg})(2556.2 - 939.4)\text{kJ/kg}\left(\frac{1000\ \text{VA}}{1\ \text{kJ/s}}\right)$$

$$\Delta t = 9186\ \text{s} \cong \mathbf{153.1\ min}$$

4–32 An insulated tank is divided into two parts by a partition. One part of the tank contains 2.5 kg of compressed liquid water at 60°C and 600 kPa while the other part is evacuated. The partition is now removed, and the water expands to fill the entire tank. Determine the final temperature of the water and the volume of the tank for a final pressure of 10 kPa.



4-32 One part of an insulated tank contains compressed liquid while the other side is evacuated. The partition is then removed, and water is allowed to expand into the entire tank. The final temperature and the volume of the tank are to be determined.

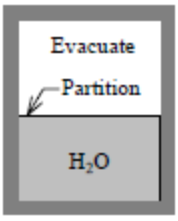
Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** The tank is insulated and thus heat transfer is negligible. **3** There are no work interactions.

Analysis We take the entire contents of 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

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

$$0 = \Delta U = m(u_2 - u_1) \quad (\text{since } W = Q = \text{KE} = \text{PE} = 0)$$

$$u_1 = u_2$$



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

$$\left.\begin{array}{l} P_1 = 600 \text{ kPa} \\ T_1 = 60°\text{C} \end{array}\right\} \begin{array}{l} v_1 \cong v_{f@60°C} = 0.001017 \text{ m}^3/\text{kg} \\ u_1 \cong u_{f@60°C} = 251.16 \text{ kJ/kg} \end{array}$$

We now assume the final state in the tank is saturated liquid-vapor mixture and determine quality. This assumption will be verified if we get a quality between 0 and 1.

$$\left.\begin{array}{l} P_2 = 10 \text{ kPa} \\ (u_2 = u_1) \end{array}\right\} \begin{array}{ll} v_f = 0.001010, & v_g = 14.670 \text{ m}^3/\text{kg} \\ u_f = 191.79, & u_{fg} = 2245.4 \text{ kJ/kg} \end{array}$$

$$x_2 = \frac{u_2 - u_f}{u_{fg}} = \frac{251.16 - 191.79}{2245.4} = 0.02644$$

Thus,

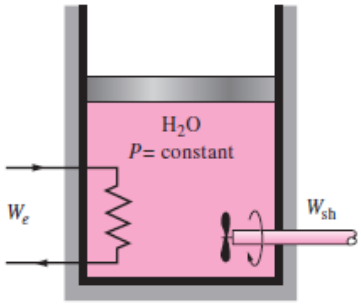
$$T_2 = = T_{sat\,@\,10\,kPa} = \mathbf{45.81\ °C}$$

$$v_2 = v_f + x_2 v_{fg} = 0.001010 + [0.02644 \times (14.670 - 0.001010)] = 0.38886 \text{ m}^3/\text{kg}$$

and,

$$V = m v_2 = (2.5 \text{ kg})(0.38886 \text{ m}^3/\text{kg}) = \mathbf{0.972\ m^3}$$

4–36 An insulated piston–cylinder device contains 5 L of saturated liquid water at a constant pressure of 175 kPa. Water is stirred by a paddle wheel while a current of 8 A flows for 45 min through a resistor placed in the water. If one-half of the liquid is evaporated during this constant-pressure process and the paddle-wheel work amounts to 400 kJ, determine the voltage of the source. Also, show the process on a P-v diagram with respect to saturation lines.
Answer: 224 V

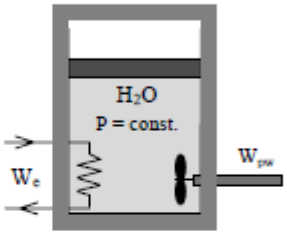


4-36 A cylinder is initially filled with saturated liquid water at a specified pressure. The water is heated electrically as it is stirred by a paddle-wheel at constant pressure. The voltage of the current source is to be determined, and the process is to be shown on a P-v diagram.

Assumptions 1 The cylinder is stationary and thus the kinetic and potential energy changes are zero. 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 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

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



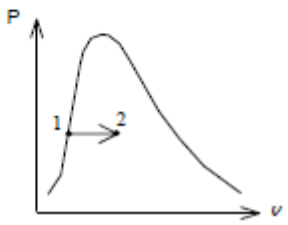
$$W_{e,in} + W_{pw,in} - W_{b,out} = \Delta U \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$
$$W_{e,in} + W_{pw,in} = m(h_2 - h_1)$$
$$(VI\Delta t) + W_{pw,in} = m(h_2 - h_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The properties of water are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 175 \text{ kPa} \\ \text{sat.liquid} \end{array}\right\} \begin{array}{l} h_1 = h_{f@175\text{ kPa}} = 487.01 \text{ kJ/kg} \\ v_1 = v_{f@175\text{ kPa}} = 0.001057 \text{ m}^3\text{/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 175 \text{ kPa} \\ x_2 = 0.5 \end{array}\right\} h_2 = h_f + x_2 h_{fg} = 487.01 + (0.5 \times 2213.1) = 1593.6 \text{ kJ/kg}$$

$$m = \frac{V_1}{v_1} = \frac{0.005 \text{ m}^3}{0.001057 \text{ m}^3\text{/kg}} = 4.731 \text{ kg}$$



Substituting,

$$VI\Delta t + (400\text{kJ}) = (4.731 \text{ kg})(1593.6 - 487.01)\text{kJ/kg}$$
$$VI\Delta t = 4835 \text{ kJ}$$
$$V = \frac{4835 \text{ kJ}}{(8 \text{ A})(45 \times 60 \text{ s})}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right) = \mathbf{223.9\ V}$$

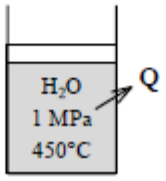
4–37 A piston–cylinder device contains steam initially at 1 MPa, 450°C, and 2.5 m^3. Steam is allowed to cool at constant pressure until it first starts condensing. Show the process on a T-v diagram with respect to saturation lines and determine (*a*) the mass of the steam, (*b*) the final temperature, and (*c*) the amount of heat transfer.

4-37 A cylinder is initially filled with steam at a specified state. The steam is cooled at constant pressure. The mass of the steam, the final temperature, and the amount of heat transfer are to be determined, and the process is to be shown on a T-v diagram.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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

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



$$-Q_{out} - W_{b,out} = \Delta U = m(u_2 - u_1) \quad \text{(since KE = PE = 0)}$$

$$-Q_{out} = m(h_2 - h_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The properties of water are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 1\text{ MPa} \\ T_2 = 450°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 0.33045\text{ m}^3/\text{kg} \\ h_1 = 3371.3\text{ kJ/kg} \end{array}$$

$$m = \frac{V_1}{v_1} = \frac{2.5\text{ m}^3}{0.33045\text{ m}^3/\text{kg}} = \mathbf{7.565\ kg}$$

(*b*) The final temperature is determined from

$$\left.\begin{array}{l} P_2 = 1\text{ MPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} T_2 = T_{sat@1\text{ MPa}} = \mathbf{179.9°C} \\ h_2 = h_{g@1\text{ MPa}} = 2777.1\text{ kJ/kg} \end{array}$$

(*c*) Substituting, the energy balance gives

$$Q_{out} = -(7.565\text{ kg})(2777.1 - 3371.3)\text{ kJ/kg} = \mathbf{4495\ kJ}$$

4–38 A piston–cylinder device initially contains steam at 200 kPa, 200°C, and 0.5 m^3. At this state, a linear spring ($F \propto x$) is touching the piston but exerts no force on it. Heat is now slowly transferred to the steam, causing the pressure and the volume to rise to 500 kPa and 0.6 m^3, respectively. Show the process on a P-v diagram with respect to saturation lines and determine (*a*) the final temperature, (*b*) the work done by the steam, and (*c*) the total heat transferred. *Answers:* (*a*) 1132°C, (*b*) 35 kJ, (*c*) 808 kJ

4-38 [*Also solved by EES on enclosed CD*] A cylinder equipped with an external spring is initially filled with steam at a specified state. Heat is transferred to the steam, and both the temperature and pressure rise. The final temperature, the boundary work done by the steam, and the amount of heat transfer are to be determined, and the process is to be shown on a *P*-*v* diagram.

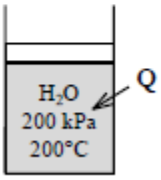
Assumptions 1 The cylinder is stationary and thus the kinetic and potential energy changes are zero. 2 The thermal energy stored in the cylinder itself is negligible. 3 The compression or expansion process is quasi-equilibrium. 4 The spring is a linear spring.

Analysis We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. Noting that the spring is not part of the system (it is external), the energy balance for this stationary closed system can be expressed as

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

$$Q_{in} - W_{b,out} = \Delta U = m(u_2 - u_1) \quad \text{(since KE = PE = 0)}$$

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



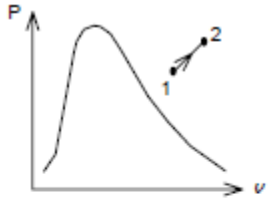
The properties of steam are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 200°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 1.08049 \text{ m}^3/\text{kg} \\ u_1 = 2654.6 \text{ kJ/kg} \end{array}$$

$$m = \frac{V_1}{v_1} = \frac{0.5 \text{ m}^3}{1.08049 \text{ m}^3/\text{kg}} = 0.4628 \text{ kg}$$

$$v_2 = \frac{V_2}{m} = \frac{0.6 \text{ m}^3}{0.4628 \text{ kg}} = 1.2966 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_2 = 500 \text{ kPa} \\ v_2 = 1.2966 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{l} T_2 = \mathbf{1132°C} \\ u_2 = 4325.2 \text{ kJ/kg} \end{array}$$



(*b*) The pressure of the gas changes linearly with volume, and thus the process curve on a P-V diagram will be a straight line. The boundary work during this process is simply the area under the process curve, which is a trapezoidal. Thus,

$$W_b = Area = \frac{P_1 + P_2}{2}(V_2 - V_1) = \frac{(200+500)\text{kPa}}{2}(0.6-0.5)\text{m}^3\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = \mathbf{35 \text{ kJ}}$$

(*c*) From the energy balance we have

$$Q_{in} = (0.4628 \text{ kg})(4325.2 - 2654.6)\text{kJ/kg} + 35 \text{ kJ} = \mathbf{808 \text{ kJ}}$$

4–40 A piston–cylinder device initially contains 0.8 m^3 of saturated water vapor at 250 kPa. At this state, the piston is resting on a set of stops, and the mass of the piston is such that a pressure of 300 kPa is required to move it. Heat is now slowly transferred to the steam until the volume doubles. Show the process on a *P*-*v* diagram with respect to saturation lines and determine (*a*) the final temperature, (*b*) the work done during this process, and (*c*) the total heat transfer. *Answers:* (*a*) 662°C, (*b*) 240 kJ, (*c*) 1213 kJ

4-40 A cylinder equipped with a set of stops for the piston to rest on is initially filled with saturated water vapor at a specified pressure. Heat is transferred to water until the volume doubles. The final temperature, the boundary work done by the steam, and the amount of heat transfer are to be determined, and the process is to be shown on a P-v diagram.

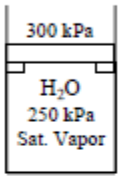
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

Analysis 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

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

$$Q_{in} - W_{b,out} = \Delta U = m(u_3 - u_1) \quad (\text{since KE} = \text{PE} = 0)$$

$$Q_{in} = m(u_3 - u_1) + W_{b,out}$$



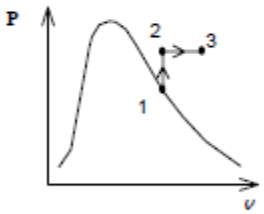
The properties of steam are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 250 \text{ kPa} \\ sat.vapor \end{array}\right\} \begin{array}{l} v_1 = v_{g@250\text{ kPa}} = 0.71873 \text{ m}^3/\text{kg} \\ u_1 = u_{g@250\text{ kPa}} = 2536.8 \text{ kJ/kg} \end{array}$$

$$m = \frac{V_1}{v_1} = \frac{0.8 \text{ m}^3}{0.71873 \text{ m}^3/\text{kg}} = 1.113 \text{ kg}$$

$$v_3 = \frac{V_3}{m} = \frac{1.6 \text{ m}^3}{1.113 \text{ kg}} = 1.4375 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} P_3 = 300 \text{ kPa} \\ v_3 = 1.4375 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{l} T_3 = \mathbf{662°C} \\ u_3 = 3411.4 \text{ kJ/kg} \end{array}$$



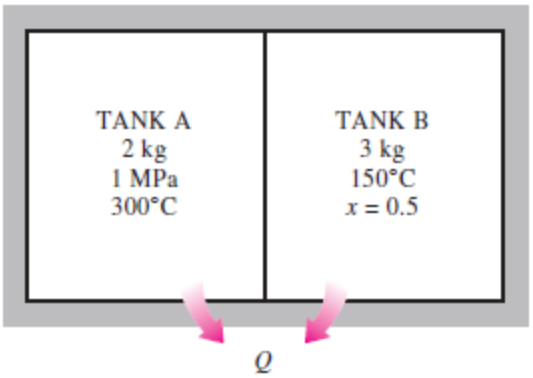
(*b*) The work done during process 1-2 is zero (since V= const) and the work done during the constant pressure process 2-3 is

$$W_{b,out} = \int_2^3 P\,dV = P(V_3 - V_2) = (300 \text{ kPa})(1.6 - 0.8)\text{m}^3\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = \mathbf{240 \text{ kJ}}$$

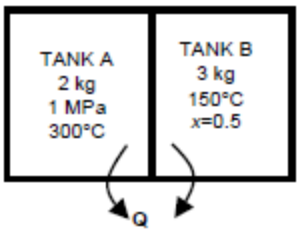
(*c*) Heat transfer is determined from the energy balance,

$$Q_{in} = m(u_3 - u_1) + W_{b,out}$$
$$= (1.113 \text{ kg})(3411.4 - 2536.8) \text{ kJ/kg} + 240 \text{ kJ} = \mathbf{1213 \text{ kJ}}$$

4–41 Two tanks (Tank A and Tank B) are separated by a partition. Initially Tank A contains 2-kg steam at 1 MPa and 300°C while Tank B contains 3-kg saturated liquid–vapor mixture with a vapor mass fraction of 50 percent. Now the partition is removed and the two sides are allowed to mix until the mechanical and thermal equilibrium are established. If the pressure at the final state is 300 kPa, determine (*a*) the temperature and quality of the steam (if mixture) at the final state and (b) the amount of heat lost from the tanks.



4-41 Two tanks initially separated by a partition contain steam at different states. Now the partition is removed and they are allowed to mix until equilibrium is established. The temperature and quality of the steam at the final state and the amount of heat lost from the tanks 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*) We take the contents of both tanks 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

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

$$-Q_{out} = \Delta U_A + \Delta U_B = [m(u_2 - u_1)]_A + [m(u_2 - u_1)]_B \quad (\text{since } W = \text{KE} = \text{PE} = 0)$$

The properties of steam in both tanks at the initial state are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_{1,A} = 1000 \text{ kPa} \\ T_{1,A} = 300°\text{C} \end{array}\right\} \begin{array}{l} v_{1,A} = 0.25799 \text{ m}^3/\text{kg} \\ u_{1,A} = 2793.7 \text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} T_{1,B} = 150°\text{C} \\ x_1 = 0.50 \end{array}\right\} \begin{array}{ll} v_f = 0.001091, & v_g = 0.39248 \text{ m}^3/\text{kg} \\ u_f = 631.66, & u_{fg} = 1927.4 \text{ kJ/kg} \end{array}$$

$$v_{1,B} = v_f + x_1 v_{fg} = 0.001091 + [0.50 \times (0.39248 - 0.001091)] = 0.19679 \text{ m}^3/\text{kg}$$

$$u_{1,B} = u_f + x_1 u_{fg} = 631.66 + (0.50 \times 1927.4) = 1595.4 \text{ kJ/kg}$$

The total volume and total mass of the system are

$$V = V_A + V_B = m_A v_{1,A} + m_B v_{1,B} = (2 \text{ kg})(0.25799 \text{ m}^3/\text{kg}) + (3 \text{ kg})(0.19679 \text{ m}^3/\text{kg}) = 1.106 \text{ m}^3$$

$$m = m_A + m_B = 3 + 2 = 5 \text{ kg}$$

Now, the specific volume at the final state may be determined

$$v_2 = \frac{V}{m} = \frac{1.106 \text{ m}^3}{5 \text{ kg}} = 0.22127 \text{ m}^3/\text{kg}$$

which fixes the final state and we can determine other properties

$$T_2 = T_{\text{sat @ 300 kPa}} = \mathbf{133.5°C}$$

$$\left.\begin{array}{l} P_2 = 300 \text{ kPa} \\ v_2 = 0.22127 \text{ m}^3/\text{kg} \end{array}\right\} x_2 = \frac{v_2 - v_f}{v_g - v_f} = \frac{0.22127 - 0.001073}{0.60582 - 0.001073} = \mathbf{0.3641}$$

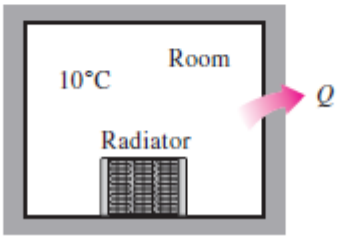
$$u_2 = u_f + x_2 u_{fg} = 561.11 + (0.3641 \times 1982.1) = 1282.8 \text{ kJ/kg}$$

(*b*) Substituting,

$$-Q_{out} = \Delta U_A + \Delta U_B = [m(u_2 - u_1)]_A + [m(u_2 - u_1)]_B$$
$$= (2 \text{ kg})(1282.8 - 2793.7)\text{kJ/kg} + (3 \text{ kg})(1282.8 - 1595.4)\text{kJ/kg} = -3959 \text{ kJ}$$

or $\quad Q_{out} = \mathbf{3959 \text{ kJ}}$

4–42 A 30-L electrical radiator containing heating oil is placed in a 50-m³ room. Both the room and the oil in the radiator are initially at 10°C. The radiator with a rating of 1.8 kW is now turned on. At the same time, heat is lost from the room at an average rate of 0.35 kJ/s. After some time, the average temperature is measured to be 20°C for the air in the room, and 50°C for the oil in the radiator. Taking the density and the specific heat of the oil to be 950 kg/m³ and 2.2 kJ/kg · °C, respectively, determine how long the heater is kept on. Assume the room is well-sealed so that there are no air leaks.

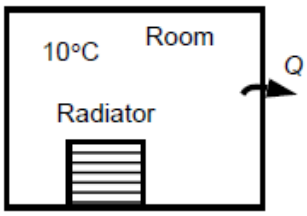


4-42 A room is heated by an electrical radiator containing heating oil. Heat is lost from the room. The time period during which the heater is on is to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **4** The local atmospheric pressure is 100 kPa. **5** The room is air-tight so that no air leaks in and out during the process.

Properties The gas constant of air is $R = 0.287$ kPa.m³/kg.K (Table A-1). Also, $c_v = 0.718$ kJ/kg.K for air at room temperature (Table A-2). Oil properties are given to be $\rho = 950$ kg/m³ and $c_p = 2.2$ kJ/kg.°C.

Analysis We take the air in the room and the oil in the radiator to be the system. This is a closed system since no mass crosses the system boundary. The energy balance for this stationary constant-volume closed system can be expressed as



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

$$(\dot{W}_{in} - \dot{Q}_{out})\Delta t = \Delta U_{air} + \Delta U_{oil}$$

$$\cong [mc_v(T_2 - T_1)]_{air} + [mc_p(T_2 - T_1)]_{oil} \quad (\text{since KE} = \text{PE} = 0)$$

The mass of air and oil are

$$m_{air} = \frac{PV_{air}}{RT_1} = \frac{(100\text{ kPa})(50\text{ m}^3)}{(0.287\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(10+273\text{ K})} = 62.32\text{ kg}$$

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

Substituting,

$$(1.8 - 0.35\text{ kJ/s})\Delta t = (62.32\text{ kg})(0.718\text{ kJ/kg}\cdot°\text{C})(20-10)°\text{C} + (28.50\text{ kg})(2.2\text{ kJ/kg}\cdot°\text{C})(50-10)°\text{C}$$

$$\longrightarrow \Delta t = \mathbf{2038\ s = 34.0\ min}$$

Discussion In practice, the pressure in the room will remain constant during this process rather than the volume, and some air will leak out as the air expands. As a result, the air in the room will undergo a constant pressure expansion process. Therefore, it is more proper to be conservative and to using ΔH instead of use ΔU in heating and air-conditioning applications.

4–56 A 3-m^3 rigid tank contains hydrogen at 250 kPa and 550 K. The gas is now cooled until its temperature drops to 350 K. Determine (*a*) the final pressure in the tank and (*b*) the amount of heat transfer.

4-56 The hydrogen gas in a rigid tank is cooled until its temperature drops to 300 K. The final pressure in the tank and the amount of heat transfer are to be determined.

Assumptions **1** Hydrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -240°C and 1.30 MPa. **2** The tank is stationary, and thus the kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$.

Properties The gas constant of hydrogen is R = 4.124 kPa.m^3/kg.K (Table A-1). The constant volume specific heat of hydrogen at the average temperature of 450 K is , $c_{v,avg}$ = 10.377 kJ/kg.K (Table A-2).

Analysis (*a*) The final pressure of hydrogen can be determined from the ideal gas relation,

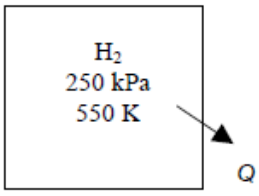
$$\frac{P_1 V}{T_1} = \frac{P_2 V}{T_2} \longrightarrow P_2 = \frac{T_2}{T_1} P_1 = \frac{350\text{ K}}{550\text{ K}}(250\text{ kPa}) = \mathbf{159.1\ kPa}$$

(*b*) We take the hydrogen in the tank 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

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

$$-Q_{out} = \Delta U$$

$$Q_{out} = -\Delta U = -m(u_2 - u_1) \cong mC_v(T_1 - T_2)$$



where

$$m = \frac{P_1 V}{RT_1} = \frac{(250\text{ kPa})(3.0\text{ m}^3)}{(4.124\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(550\text{ K})} = 0.3307\text{ kg}$$

Substituting into the energy balance,

Q_{out} = (0.33307 kg)(10.377 kJ/kg·K)(550 - 350)K = **686.2 kJ**

4–57 A 4-m × 5-m × 6-m room is to be heated by a baseboard resistance heater. It is desired that the resistance heater be able to raise the air temperature in the room from 7 to 23°C within 15 min. Assuming no heat losses from the room and an atmospheric pressure of 100 kPa, determine the required power of the resistance heater. Assume constant specific heats at room temperature. *Answer:* 1.91 kW

4-57 A resistance heater is to raise the air temperature in the room from 7 to 23°C within 15 min. The required power rating of the resistance heater is to be determined.

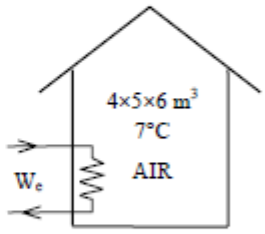
Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **4** Heat losses from the room are negligible. **5** The room is air-tight so that no air leaks in and out during the process.

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

Analysis We take the air in the room to be the system. This is a closed system since no mass crosses the system boundary. The energy balance for this stationary constant-volume closed system can be expressed as

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

$$W_{e,in} = \Delta U \cong mc_{v,avg}(T_2 - T_1) \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$



or,

$$\dot{W}_{e,in}\Delta t = mc_{v,avg}(T_2 - T_1)$$

The mass of air is

$$V = 4 \times 5 \times 6 = 120 \text{ m}^3$$

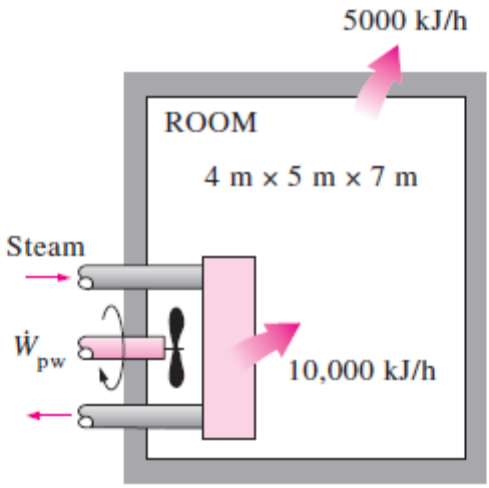
$$m = \frac{P_1 V}{RT_1} = \frac{(100 \text{ kPa})(120 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(280 \text{ K})} = 149.3 \text{ kg}$$

Substituting, the power rating of the heater becomes

$$\dot{W}_{e,in} = \frac{(149.3 \text{ kg})(0.718 \text{ kJ/kg}\cdot{}^\circ\text{C})(23-7)^\circ\text{C}}{15 \times 60 \text{ s}} = \mathbf{1.91 \text{ kW}}$$

Discussion In practice, the pressure in the room will remain constant during this process rather than the volume, and some air will leak out as the air expands. As a result, the air in the room will undergo a constant pressure expansion process. Therefore, it is more proper to be conservative and to use ΔH instead of using ΔU in heating and air-conditioning applications.

4–58 A 4-m × 5-m × 7-m room is heated by the radiator of a steam-heating system. The steam radiator transfers heat



at a rate of 10,000 kJ/h, and a 100-W fan is used to distribute the warm air in the room. The rate of heat loss from the room is estimated to be about 5000 kJ/h. If the initial temperature of the room air is 10°C, determine how long it will take for the air temperature to rise to 20°C. Assume constant specific heats at room temperature.

4-58 A room is heated by a radiator, and the warm air is distributed by a fan. Heat is lost from the room. The time it takes for the air temperature to rise to 20°C is to be determined.

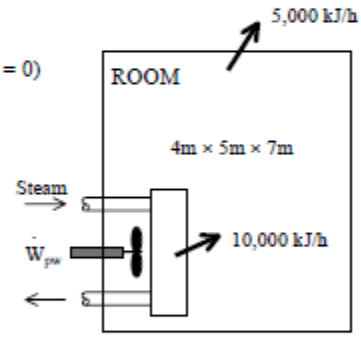
Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **4** The local atmospheric pressure is 100 kPa. **5** The room is air-tight so that no air leaks in and out during the process.

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

Analysis We take the air in the room to be the system. This is a closed system since no mass crosses the system boundary. The energy balance for this stationary constant-volume closed system can be expressed as

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

$$Q_{in} + W_{fan,in} - Q_{out} = \Delta U \cong mc_{v,avg}(T_2 - T_1) \quad (\text{since } KE = PE = 0)$$



or,

$$(\dot{Q}_{in} + \dot{W}_{fan,in} - \dot{Q}_{out})\Delta t = mc_{v,avg}(T_2 - T_1)$$

The mass of air is

$$V = 4 \times 5 \times 7 = 140 \text{ m}^3$$

$$m = \frac{P_1 V}{RT_1} = \frac{(100 \text{ kPa})(140 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(283 \text{ K})} = 172.4 \text{ kg}$$

Using the c_v value at room temperature,

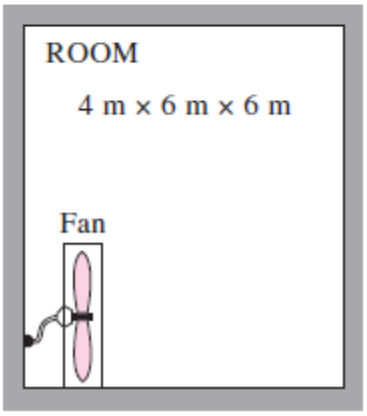
$$[(10{,}000 - 5{,}000)/3600 \text{ kJ/s} + 0.1 \text{ kJ/s}]\Delta t = (172.4 \text{ kg})(0.718 \text{ kJ/kg}\cdot{}^\circ\text{C})(20 - 10)^\circ\text{C}$$

It yields

$$\Delta t = 831 \text{ s}$$

Discussion In practice, the pressure in the room will remain constant during this process rather than the volume, and some air will leak out as the air expands. As a result, the air in the room will undergo a constant pressure expansion process. Therefore, it is more proper to be conservative and to using ΔH instead of use ΔU in heating and air-conditioning applications.

4–59 A student living in a 4-m × 6-m × 6-m dormitory room turns on her 150-W fan before she leaves the room on a summer day, hoping that the room will be cooler when she comes back in the evening. Assuming all the doors and windows are tightly closed and disregarding any heat transfer through the walls and the windows, determine the temperature in the room when she comes back 10 h later. Use specific heat values at room temperature, and assume the room to be at 100 kPa and 15°C in the morning when she leaves.
Answer: 58.2°C



4-59 A student living in a room turns her 150-W fan on in the morning. The temperature in the room when she comes back 10 h later is to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **4** All the doors and windows are tightly closed, and heat transfer through the walls and the windows is disregarded.

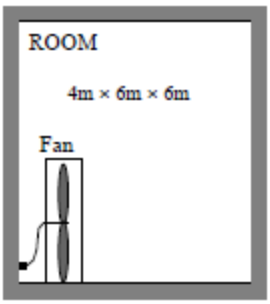
Properties The gas constant of air is $R = 0.287$ kPa.m^3/kg.K (Table A-1). Also, $c_v = 0.718$ kJ/kg.K for air at room temperature (Table A-2).

Analysis We take the room as the system. This is a *closed system* since the doors and the windows are said to be tightly closed, and thus no mass crosses the system boundary during the process. The energy balance for this system can be expressed as

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

$$W_{e,in} = \Delta U$$

$$W_{e,in} = m(u_2 - u_1) \cong mc_v(T_2 - T_1)$$



The mass of air is

$$V = 4 \times 6 \times 6 = 144 \text{ m}^3$$

$$m = \frac{P_1 V}{RT_1} = \frac{(100 \text{ kPa})(144 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(288 \text{ K})} = 174.2 \text{ kg}$$

The electrical work done by the fan is

$$W_e = \dot{W}_e \Delta t = (0.15 \text{ kJ/s})(10 \times 3600 \text{ s}) = 5400 \text{ kJ}$$

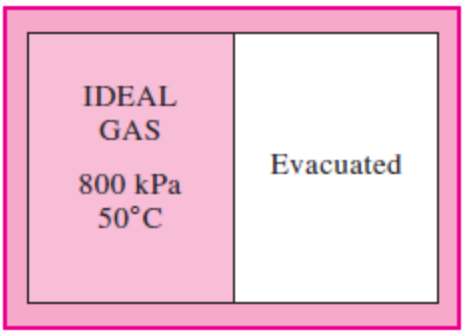
Substituting and using the c_v value at room temperature,

$$5400 \text{ kJ} = (174.2 \text{ kg})(0.718 \text{ kJ/kg}\cdot°\text{C})(T_2 - 15)°\text{C}$$

$$T_2 = \mathbf{58.2°C}$$

Discussion Note that a fan actually causes the internal temperature of a confined space to rise. In fact, a 100-W fan supplies a room with as much energy as a 100-W resistance heater.

4–61 An insulated rigid tank is divided into two equal parts by a partition. Initially, one part contains 4 kg of an ideal gas at 800 kPa and 50°C, and the other part is evacuated. The partition is now removed, and the gas expands into the entire tank. Determine the final temperature and pressure in the tank.



4-61 One part of an insulated rigid tank contains an ideal gas while the other side is evacuated. The final temperature and pressure in the tank are to be determined when the partition is removed.

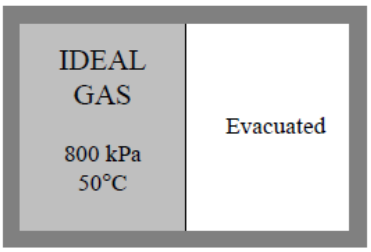
Assumptions **1** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **2** The tank is insulated and thus heat transfer is negligible.

Analysis We take the entire tank as the system. This is a *closed system* since no mass crosses the boundaries of the system. The energy balance for this system can be expressed as

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

$$0 = \Delta U = m(u_2 - u_1)$$

$$u_2 = u_1$$



Therefore,

$$T_2 = T_1 = \mathbf{50°C}$$

Since $u = u(T)$ for an ideal gas. Then,

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \longrightarrow P_2 = \frac{V_1}{V_2}P_1 = \frac{1}{2}(800 \text{ kPa}) = \mathbf{400\ kPa}$$

4–62 A piston–cylinder device whose piston is resting on top of a set of stops initially contains 0.5 kg of helium gas at 100 kPa and 25°C. The mass of the piston is such that 500 kPa of pressure is required to raise it. How much heat must be transferred to the helium before the piston starts rising? *Answer:* 1857 kJ

4-62 A cylinder equipped with a set of stops for the piston to rest on is initially filled with helium gas at a specified state. The amount of heat that must be transferred to raise the piston is to be determined.

Assumptions **1** Helium is an ideal gas with constant specific heats. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** There are no work interactions involved. **4** The thermal energy stored in the cylinder itself is negligible.

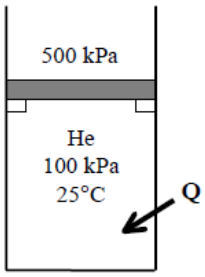
Properties The specific heat of helium at room temperature is $c_v = 3.1156$ kJ/kg.K (Table A-2).

Analysis We take the helium gas in the cylinder as the system. This is a closed system since no mass crosses the boundary of the system. The energy balance for this constant volume closed system can be expressed as

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

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

$$Q_{in} = m(u_2 - u_1) = mc_v(T_2 - T_1)$$



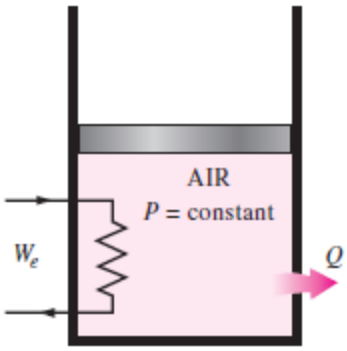
The final temperature of helium can be determined from the ideal gas relation to be

$$\frac{P_1V}{T_1} = \frac{P_2V}{T_2} \longrightarrow T_2 = \frac{P_2}{P_1}T_1 = \frac{500 \text{ kPa}}{100 \text{ kPa}}(298 \text{ K}) = 1490 \text{ K}$$

Substituting into the energy balance relation gives

Q_{in} = (0.5 kg)(3.1156 kJ/kg·K)(1490 - 298)K = **1857 kJ**

4–65 A mass of 15 kg of air in a piston–cylinder device is heated from 25 to 77°C by passing current through a resistance heater inside the cylinder. The pressure inside the cylinder is held constant at 300 kPa during the process, and a heat loss of 60 kJ occurs. Determine the electric energy supplied, in kWh.
Answer: 0.235 kWh



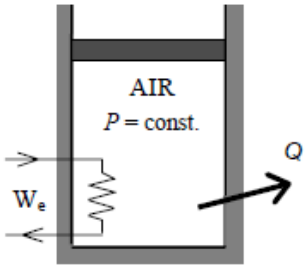
4-65 A cylinder is initially filled with air at a specified state. Air is heated electrically at constant pressure, and some heat is lost in the process. The amount of electrical energy supplied is to be determined. √

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** Air is an ideal gas with variable specific heats. **3** The thermal energy stored in the cylinder itself and the resistance wires is negligible. **4** The compression or expansion process is quasi-equilibrium.

Properties The initial and final enthalpies of air are (Table A-17)

$$h_1 = h_{@\,298\,\mathrm{K}} = 298.18\ \mathrm{kJ/kg}$$

$$h_2 = h_{@\,350\,\mathrm{K}} = 350.49\ \mathrm{kJ/kg}$$



Analysis 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

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

$$W_{\mathrm{e,in}} - Q_{\mathrm{out}} - W_{\mathrm{b,out}} = \Delta U \longrightarrow W_{\mathrm{e,in}} = m(h_2 - h_1) + Q_{\mathrm{out}}$$

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

$$W_{\mathrm{e,in}} = (15\ \mathrm{kg})(350.49 - 298.18)\mathrm{kJ/kg} + (60\ \mathrm{kJ}) = 845\ \mathrm{kJ}$$

or, $$W_{e,in} = (845\mathrm{kJ})\left(\frac{1\ \mathrm{kWh}}{3600\ \mathrm{kJ}}\right) = \mathbf{0.235\ kWh}$$

Alternative solution The specific heat of air at the average temperature of $T_{avg} = (25+77)/2 = 51°\mathrm{C} = 324$ K is, from Table A-2b, $c_{p,avg} = 1.0065$ kJ/kg.°C. Substituting,

$$W_{\mathrm{e,in}} = mc_p(T_2 - T_1) + Q_{\mathrm{out}} = (15\ \mathrm{kg})(1.0065\ \mathrm{kJ/kg.°C})(77 - 25)°\mathrm{C} + 60\ \mathrm{kJ} = 845\ \mathrm{kJ}$$

or, $$W_{\mathrm{e,in}} = (845\ \mathrm{kJ})\left(\frac{1\ \mathrm{kWh}}{3600\ \mathrm{kJ}}\right) = \mathbf{0.235\ kWh}$$

Discussion Note that for small temperature differences, both approaches give the same result.

4–66 An insulated piston–cylinder device initially contains 0.3 m³ of carbon dioxide at 200 kPa and 27°C. An electric switch is turned on, and a 110-V source supplies current to a resistance heater inside the cylinder for a period of 10 min. The pressure is held constant during the process, while the volume is doubled. Determine the current that passes through the resistance heater.

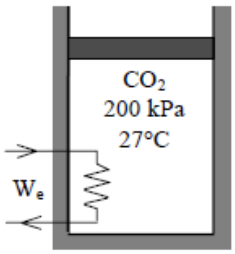
4-66 An insulated cylinder initially contains CO_2 at a specified state. The CO_2 is heated electrically for 10 min at constant pressure until the volume doubles. The electric current is to be determined.

Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** The CO_2 is an ideal gas with constant specific heats. **3** The thermal energy stored in the cylinder itself and the resistance wires is negligible. **4** The compression or expansion process is quasi-equilibrium.

Properties The gas constant and molar mass of CO_2 are R = 0.1889 kPa.m³/kg.K and M = 44 kg/kmol (Table A-1). The specific heat of CO_2 at the average temperature of T_{avg} = (300 + 600)/2 = 450 K is $c_{p,avg}$ = 0.978 kJ/kg.°C (Table A-2b).

Analysis 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

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



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

$$W_{e,in} = m(h_2 - h_1) \cong mc_p(T_2 - T_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process. The final temperature of CO_2 is

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \longrightarrow T_2 = \frac{P_2}{P_1}\frac{V_2}{V_1}T_1 = 1 \times 2 \times (300\text{ K}) = 600\text{ K}$$

The mass of CO_2 is

$$m = \frac{P_1V_1}{RT_1} = \frac{(200\text{ kPa})(0.3\text{ m}^3)}{(0.1889\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})} = 1.059\text{ kg}$$

Substituting,

$$W_{e,in} = (1.059\text{ kg})(0.978\text{ kJ/kg.K})(600 - 300)\text{K} = 311\text{ kJ}$$

Then,

$$I = \frac{W_{e,in}}{V\Delta t} = \frac{311\text{ kJ}}{(110\text{V})(10 \times 60\text{ s})}\left(\frac{1000\text{ VA}}{1\text{ kJ/s}}\right) = \mathbf{4.71\ A}$$

4–72 A piston–cylinder device, whose piston is resting on a set of stops, initially contains 3 kg of air at 200 kPa and 27°C. The mass of the piston is such that a pressure of 400 kPa is required to move it. Heat is now transferred to the air until its volume doubles. Determine the work done by the air and the total heat transferred to the air during this process. Also show the process on a P-V diagram. *Answers:* 516 kJ, 2674 kJ

4-72 A cylinder equipped with a set of stops for the piston is initially filled with air at a specified state. Heat is transferred to the air until the volume doubled. The work done by the air and the amount of heat transfer are to be determined, and the process is to be shown on a P-v diagram.

Assumptions **1** Air is an ideal gas with variable specific heats. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

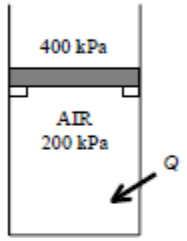
Properties The gas constant of air is $R = 0.287$ kPa.m^3/kg.K (Table A-1).

Analysis We take the air in the cylinder as the system. This is a closed system since no mass crosses the boundary of the system. The energy balance for this closed system can be expressed as

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

$$Q_{in} - W_{b,out} = \Delta U = m(u_3 - u_1)$$

$$Q_{in} = m(u_3 - u_1) + W_{b,out}$$

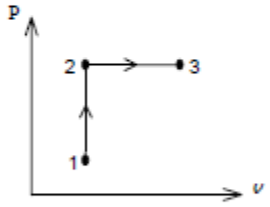


The initial and the final volumes and the final temperature of air are

$$V_1 = \frac{mRT_1}{P_1} = \frac{(3\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})}{200\text{ kPa}} = 1.29\text{ m}^3$$

$$V_3 = 2V_1 = 2\times 1.29 = 2.58\text{ m}^3$$

$$\frac{P_1V_1}{T_1} = \frac{P_3V_3}{T_3} \longrightarrow T_3 = \frac{P_3}{P_1}\frac{V_3}{V_1}T_1 = \frac{400\text{ kPa}}{200\text{ kPa}}\times 2\times(300\text{ K}) = 1200\text{ K}$$



No work is done during process 1-2 since $V_1 = V_2$. The pressure remains constant during process 2-3 and the work done during this process is

$$W_{b,out} = \int_1^2 P\,dV = P_2(V_3 - V_2) = (400\text{ kPa})(2.58 - 1.29)\text{m}^3 = \mathbf{516\ kJ}$$

The initial and final internal energies of air are (Table A-17)

$$u_1 = u_{@300\text{ K}} = 214.07\text{ kJ/kg}$$

$$u_3 = u_{@1200\text{ K}} = 933.33\text{ kJ/kg}$$

Then from the energy balance,

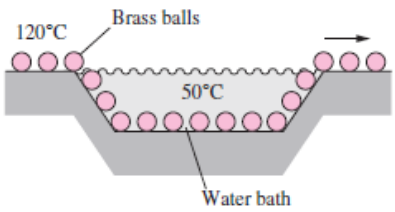
$$Q_{in} = (3\text{ kg})(933.33 - 214.07)\text{kJ/kg} + 516\text{ kJ} = \mathbf{2674\ kJ}$$

Alternative solution The specific heat of air at the average temperature of $T_{avg} = (300 + 1200)/2 = 750$ K is, from Table A-2b, $c_{v,avg} = 0.800$ kJ/kg.K. Substituting,

$$Q_{in} = m(u_3 - u_1) + W_{b,out} \cong mc_v(T_3 - T_1) + W_{b,out}$$

$$Q_{in} = (3\text{ kg})(0.800\text{ kJ/kg.K})(1200 - 300)\text{ K} + 516\text{ kJ} = \mathbf{2676\ kJ}$$

4–74 In a manufacturing facility, 5-cm-diameter brass balls ($\rho = 8522$ kg/m^3 and $c_p = 0.385$ kJ/kg · °C) initially at 120°C are quenched in a water bath at 50°C for a period of 2 min at a rate of 100 balls per minute. If the temperature of the balls after quenching is 74°C, determine the rate at which heat needs to be removed from the water in order to keep its temperature constant at 50°C.



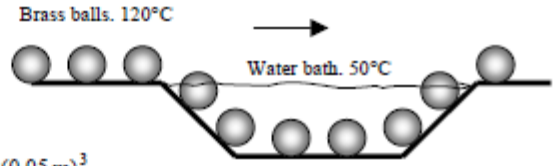
4-74 A number of brass balls are to be quenched in a water bath at a specified rate. The rate at which heat needs to be removed from the water in order to keep its temperature constant is to be determined.

Assumptions **1** The thermal properties of the balls are constant. **2** The balls are at a uniform temperature before and after quenching. **3** The changes in kinetic and potential energies are negligible.

Properties The density and specific heat of the brass balls are given to be $\rho = 8522$ kg/m^3 and $c_p = 0.385$ kJ/kg.°C.

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

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



$$-Q_{out} = \Delta U_{ball} = m(u_2 - u_1)$$
$$Q_{out} = mC(T_1 - T_2)$$

The total amount of heat transfer from a ball is

$$m = \rho V = \rho \frac{\pi D^3}{6} = (8522\ \text{kg/m}^3)\frac{\pi(0.05\ \text{m})^3}{6} = 0.558\ \text{kg}$$

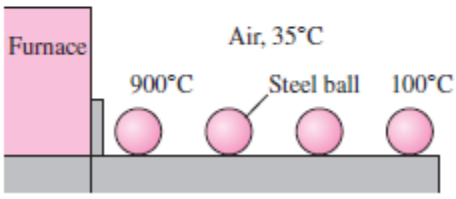
$$Q_{out} = mc(T_1 - T_2) = (0.558\ \text{kg})(0.385\ \text{kJ/kg.°C})(120 - 74)\text{°C} = 9.88\ \text{kJ/ball}$$

Then the rate of heat transfer from the balls to the water becomes

$$\dot{Q}_{total} = \dot{n}_{ball} Q_{ball} = (100\ \text{balls/min}) \times (9.88\ \text{kJ/ball}) = \mathbf{988\ kJ/min}$$

Therefore, heat must be removed from the water at a rate of 988 kJ/min in order to keep its temperature constant at 50°C since energy input must be equal to energy output for a system whose energy level remains constant. That is, $E_{in} = E_{out}$ when $\Delta E_{system} = 0$

4–79 Carbon steel balls (ρ = 7833 kg/m^3 and c_p = 0.465 kJ/kg · °C) 8 mm in diameter are annealed by heating them first to 900°C in a furnace, and then allowing them to cool slowly to 100°C in ambient air at 35°C. If 2500 balls are to be annealed per hour, determine the total rate of heat transfer from the balls to the ambient air. *Answer:* 542 W



4-79 Carbon steel balls are to be annealed at a rate of 2500/h by heating them first and then allowing them to cool slowly in ambient air at a specified rate. The total rate of heat transfer from the balls to the ambient air is to be determined.

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

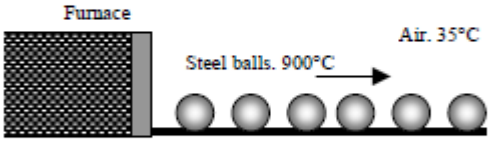
Properties The density and specific heat of the balls are given to be ρ = 7833 kg/m^3 and c_p = 0.465 kJ/kg.°C.

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

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

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

$$Q_{out} = mc(T_1 - T_2)$$



(*b*) The amount of heat transfer from a single ball is

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

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

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

$$\dot{Q}_{out} = \dot{n}_{ball}Q_{out} = (2500\,\text{balls/h}) \times (0.781\,\text{kJ/ball}) = 1{,}953\,\text{kJ/h} = \mathbf{542}\,\text{W}$$

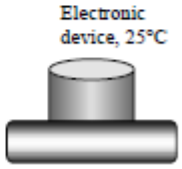
4–80 An electronic device dissipating 30 W has a mass of 20 g and a specific heat of 850 J/kg · °C. The device is lightly used, and it is on for 5 min and then off for several hours, during which it cools to the ambient temperature of 25°C. Determine the highest possible temperature of the device at the end of the 5-min operating period. What would your answer be if the device were attached to a 0.2-kg aluminum heat sink? Assume the device and the heat sink to be nearly isothermal.

4-80 An electronic device is on for 5 minutes, and off for several hours. The temperature of the device at the end of the 5-min operating period is to be determined for the cases of operation with and without a heat sink.

Assumptions **1** The device and the heat sink are isothermal. **2** The thermal properties of the device and of the sink are constant. **3** Heat loss from the device during on time is disregarded since the highest possible temperature is to be determined.

Properties The specific heat of the device is given to be $c_p = 850$ J/kg.°C. The specific heat of aluminum at room temperature of 300 K is 902 J/kg.°C (Table A-3).

Analysis We take the device to be the system. Noting that electrical energy is supplied, the energy balance for this closed system can be expressed as



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

$$W_{e,in} = \Delta U_{device} = m(u_2 - u_1)$$

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

Substituting, the temperature of the device at the end of the process is determined to be

$$(30\ \text{J/s})(5 \times 60\ \text{s}) = (0.020\ \text{kg})(850\ \text{J/kg.°C})(T_2 - 25)\text{°C} \quad \rightarrow \quad T_2 = \mathbf{554°C} \quad \text{(without the heat sink)}$$

Case 2 When a heat sink is attached, the energy balance can be expressed as

$$W_{e,in} = \Delta U_{device} + \Delta U_{heat\ sink}$$

$$\dot{W}_{e,in}\Delta t = mc(T_2 - T_1)_{device} + mc(T_2 - T_1)_{heat\ sink}$$

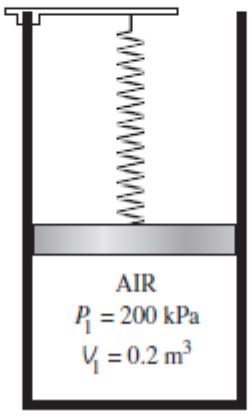
Substituting, the temperature of the device-heat sink combination is determined to be

$$(30\ \text{J/s})(5 \times 60\ \text{s}) = (0.020\ \text{kg})(850\ \text{J/kg.°C})(T_2 - 25)\text{°C} + (0.200\ \text{kg})(902\ \text{J/kg.°C})(T_2 - 25)\text{°C}$$

$$T_2 = \mathbf{70.6°C} \quad \text{(with heat sink)}$$

Discussion These are the maximum temperatures. In reality, the temperatures will be lower because of the heat losses to the surroundings.

4–114 A frictionless piston–cylinder device initially contains air at 200 kPa and 0.2 m^3. At this state, a linear spring ($F \propto x$) is touching the piston but exerts no force on it. The air is now heated to a final state of 0.5 m^3 and 800 kPa. Determine (*a*) the total work done by the air and (*b*) the work done against the spring. Also, show the process on a *P*-*V* diagram.
Answers: (*a*) 150 kJ, (*b*) 90 kJ



4-114 A cylinder equipped with an external spring is initially filled with air at a specified state. Heat is transferred to the air, and both the temperature and pressure rise. The total boundary work done by the air, and the amount of work done against the spring are to be determined, and the process is to be shown on a P-v diagram.

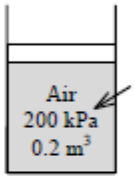
Assumptions **1** The process is quasi-equilibrium. **2** The spring is a linear spring.

Analysis (*a*) The pressure of the gas changes linearly with volume during this process, and thus the process curve on a P-V diagram will be a straight line. Then the boundary work during this process is simply the area under the process curve, which is a trapezoidal. Thus,

$$W_{b,out} = \text{Area} = \frac{P_1 + P_2}{2}(V_2 - V_1)$$

$$= \frac{(200+800)\text{kPa}}{2}(0.5-0.2)\text{m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

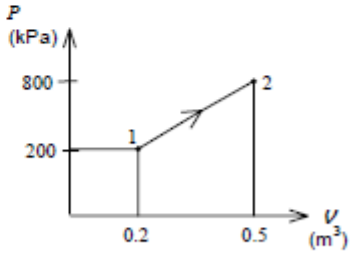
$$= \mathbf{150\ kJ}$$



(*b*) If there were no spring, we would have a constant pressure process at P = 200 kPa. The work done during this process is

$$W_{b,out,no\ spring} = \int_1^2 P\,dV = P(V_2 - V_1)$$

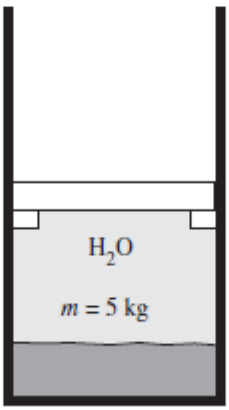
$$= (200\text{ kPa})(0.5-0.2)\text{m}^3/\text{kg}\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) = 60\text{ kJ}$$



Thus,

$$W_{spring} = W_b - W_{b,no\ spring} = 150 - 60 = \mathbf{90\ kJ}$$

4–115 A mass of 5 kg of saturated liquid–vapor mixture of water is contained in a piston–cylinder device at 125 kPa. Initially, 2 kg of the water is in the liquid phase and the rest is in



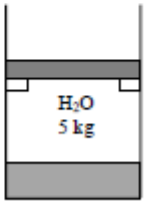
the vapor phase. Heat is now transferred to the water, and the piston, which is resting on a set of stops, starts moving when the pressure inside reaches 300 kPa. Heat transfer continues until the total volume increases by 20 percent. Determine (*a*) the initial and final temperatures, (*b*) the mass of liquid water when the piston first starts moving, and (*c*) the work done during this process. Also, show the process on a P-V diagram.

4-115 A cylinder equipped with a set of stops for the piston is initially filled with saturated liquid-vapor mixture of water a specified pressure. Heat is transferred to the water until the volume increases by 20%. The initial and final temperature, the mass of the liquid when the piston starts moving, and the work done during the process are to be determined, and the process is to be shown on a *P-v* diagram.

Assumptions The process is quasi-equilibrium.

Analysis (*a*) Initially the system is a saturated mixture at 125 kPa pressure, and thus the initial temperature is

$$T_1 = T_{\text{sat@125 kPa}} = \mathbf{106.0°C}$$



The total initial volume is

$$V_1 = m_f v_f + m_g v_g = 2 \times 0.001048 + 3 \times 1.3750 = 4.127 \text{ m}^3$$

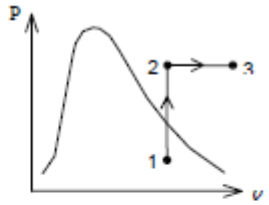
Then the total and specific volumes at the final state are

$$V_3 = 1.2V_1 = 1.2 \times 4.127 = 4.953 \text{ m}^3$$

$$v_3 = \frac{V_3}{m} = \frac{4.953 \text{ m}^3}{5 \text{ kg}} = 0.9905 \text{ m}^3/\text{kg}$$

Thus,

$$\left.\begin{array}{l} P_3 = 300 \text{ kPa} \\ v_3 = 0.9905 \text{ m}^3/\text{kg} \end{array}\right\} T_3 = \mathbf{373.6°C}$$



(*b*) When the piston first starts moving, $P_2 = 300$ kPa and $V_2 = V_1 = 4.127$ m^3. The specific volume at this state is

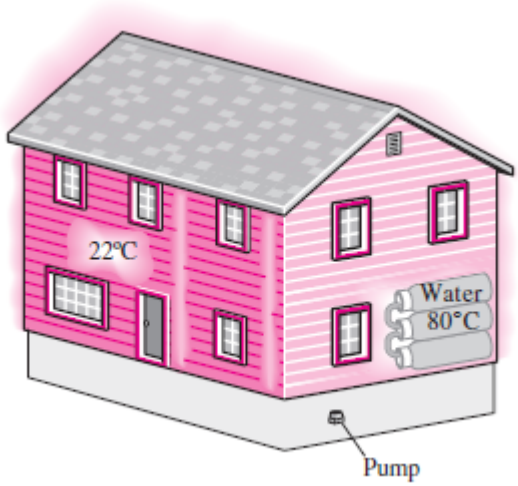
$$v_2 = \frac{V_2}{m} = \frac{4.127 \text{ m}^3}{5 \text{ kg}} = 0.8254 \text{ m}^3/\text{kg}$$

which is greater than $v_g = 0.60582$ m^3/kg at 300 kPa. Thus **no liquid** is left in the cylinder when the piston starts moving.

(*c*) No work is done during process 1-2 since $V_1 = V_2$. The pressure remains constant during process 2-3 and the work done during this process is

$$W_b = \int_2^3 P dV = P_2(V_3 - V_2) = (300 \text{ kPa})(4.953 - 4.127)\text{m}^3\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = \mathbf{247.6 \text{ kJ}}$$

4–122 A passive solar house that is losing heat to the outdoors 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 back-up electric resistance heater turns on whenever necessary to keep the house at 22°C. (*a*) How long did the electric heating system run that night? (*b*) How long would the electric heater run that night if the house incorporated no solar heating? *Answers:* (*a*) 4.77 h, (*b*) 9.26 h



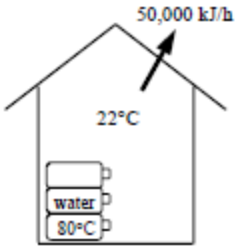
4-122 The heating of a passive solar house at night is to be assisted by solar heated water. The length of time that the electric heating system would run that night with or without solar heating are to be determined.

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 ρ = 1 kg/L and c = 4.18 kJ/kg·°C (Table A-3).

Analysis (a) 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 $\Delta t = 17{,}170\ \text{s} = \mathbf{4.77\ h}$

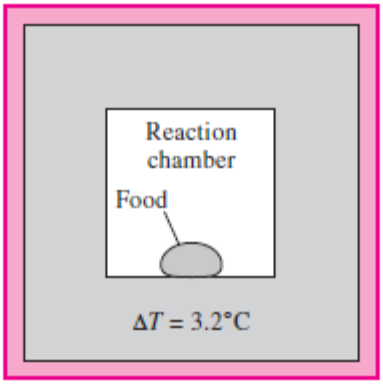
(b) If the house incorporated no solar heating, the energy balance relation above would simplify further to

$$\dot{W}_{e,in}\Delta t - Q_{out} = 0$$

Substituting, $(15\ \text{kJ/s})\Delta t - (50{,}000\ \text{kJ/h})(10\ \text{h}) = 0$

It gives $\Delta t = 33{,}333\ \text{s} = \mathbf{9.26\ h}$

4–126 The energy content of a certain food is to be determined in a bomb calorimeter that contains 3 kg of water by burning a 2-g sample of it in the presence of 100 g of air in the reaction chamber. If the water temperature rises by 3.2°C when equilibrium is established, determine the energy content of the food, in kJ/kg, by neglecting the thermal energy stored in the reaction chamber and the energy supplied by the mixer. What is a rough estimate of the error involved in neglecting the thermal energy stored in the reaction chamber?
Answer: 20,060 kJ/kg



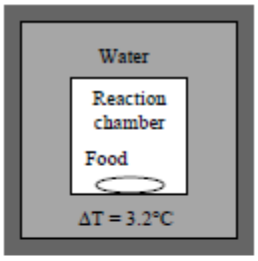
4-126 A sample of a food is burned in a bomb calorimeter, and the water temperature rises by 3.2°C when equilibrium is established. The energy content of the food is to be determined.

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 reaction chamber is negligible relative to the energy stored in water. **4** The energy supplied by the mixer is negligible.

Properties The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3). The constant volume specific heat of air at room temperature is $c_v = 0.718$ kJ/kg·°C (Table A-2).

Analysis The chemical energy released during the combustion of the sample is transferred to the water as heat. Therefore, disregarding the change in the sensible energy of the reaction chamber, the energy content of the food is simply the heat transferred to the water. Taking the water as our system, the energy balance can be written as

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



or $$Q_{in} = (\Delta U)_{water} = [mc(T_2 - T_1)]_{water}$$

Substituting, $$Q_{in} = (3\text{ kg})(4.18\text{ kJ/kg·°C})(3.2°\text{C}) = 40.13\text{ kJ}$$

for a 2-g sample. Then the energy content of the food per unit mass is

$$\frac{40.13\text{ kJ}}{2\text{ g}}\left(\frac{1000\text{ g}}{1\text{ kg}}\right) = \mathbf{20{,}060\ \ kJ/kg}$$

To make a rough estimate of the error involved in neglecting the thermal energy stored in the reaction chamber, we treat the entire mass within the chamber as air and determine the change in sensible internal energy:

$$(\Delta U)_{chamber} = [mc_v(T_2 - T_1)]_{chamber} = (0.102\text{ kg})(0.718\text{ kJ/kg·°C})(3.2°\text{C}) = 0.23\text{ kJ}$$

which is less than 1% of the internal energy change of water. Therefore, it is reasonable to disregard the change in the sensible energy content of the reaction chamber in the analysis.

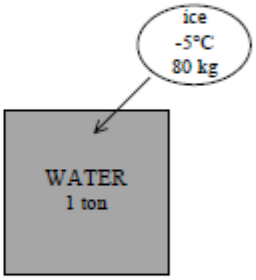
4–130 In order to cool 1 ton of water at 20°C in an insulated tank, a person pours 80 kg of ice at −5°C into the water. Determine the final equilibrium temperature in the tank. The melting temperature and the heat of fusion of ice at atmospheric pressure are 0°C and 333.7 kJ/kg, respectively.
Answer: 12.4°C

4-130 A 1- ton (1000 kg) of water is to be cooled in a tank by pouring ice into it. The final equilibrium temperature in the tank is to be determined.

Assumptions **1** Thermal properties of the ice and water are constant. **2** Heat transfer to the water tank is negligible. **3** There is no stirring by hand or a mechanical device (it will add energy).

Properties The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C, and the specific heat of ice at about 0°C is $c = 2.11$ kJ/kg·°C (Table A-3). The melting temperature and the heat of fusion of ice at 1 atm are 0°C and 333.7 kJ/kg.

Analysis We take the ice and the water as our system, and disregard any heat transfer between the system and the surroundings. Then the energy balance for this process can be written as



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

$$0 = \Delta U$$

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

$$[mc(0^\circ\text{C} - T_1)_{solid} + mh_{if} + mc(T_2 - 0^\circ\text{C})_{liquid}]_{ice} + [mc(T_2 - T_1)]_{water} = 0$$

Substituting,

$$(80\text{ kg})\{(2.11\text{ kJ/kg}\cdot^\circ\text{C})[0-(-5)]^\circ\text{C} + 333.7\text{ kJ/kg} + (4.18\text{ kJ/kg}\cdot^\circ\text{C})(T_2 - 0)^\circ\text{C}\}$$
$$+(1000\text{ kg})(4.18\text{ kJ/kg}\cdot^\circ\text{C})(T_2 - 20)^\circ\text{C} = 0$$

It gives $T_2 = \mathbf{12.4°C}$

which is the final equilibrium temperature in the tank.

4–131 An insulated piston–cylinder device initially contains 0.01 m^3 of saturated liquid–vapor mixture with a quality of 0.2 at 120°C. Now some ice at 0°C is added to the cylinder. If the cylinder contains saturated liquid at 120°C when thermal equilibrium is established, determine the amount of ice added. The melting temperature and the heat of fusion of ice at atmospheric pressure are 0°C and 333.7 kJ/kg, respectively.

4-131 An insulated cylinder initially contains a saturated liquid-vapor mixture of water at a specified temperature. The entire vapor in the cylinder is to be condensed isothermally by adding ice inside the cylinder. The amount of ice that needs to be added is to be determined.

Assumptions **1** Thermal properties of the ice are constant. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** There is no stirring by hand or a mechanical device (it will add energy).

Properties The specific heat of ice at about 0°C is c = 2.11 kJ/kg·°C (Table A-3). The melting temperature and the heat of fusion of ice at 1 atm are given to be 0°C and 333.7 kJ/kg.

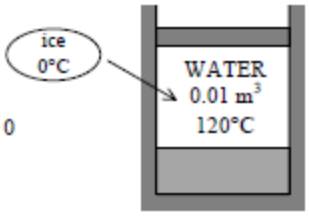
Analysis We take the contents of the cylinder (ice and saturated water) as our system, which is a closed system. Noting that the temperature and thus the pressure remains constant during this phase change process and thus $W_b + \Delta U = \Delta H$, the energy balance for this system can be written as

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

$$W_{b,in} = \Delta U \rightarrow \Delta H = 0$$

$$\Delta H_{ice} + \Delta H_{water} = 0$$

$$[mc(0^\circ\text{C} - T_1)_{solid} + mh_{if} + mc(T_2 - 0^\circ\text{C})_{liquid}]_{ice} + [m(h_2 - h_1)]_{water} = 0$$



The properties of water at 120°C are (Table A-4)

$$v_f = 0.001060, \quad v_g = 0.89133 \text{ m}^3/\text{kg}$$
$$h_f = 503.81, \quad h_{fg} = 2202.1 \text{ kJ.kg}$$

Then,

$$v_1 = v_f + x_1 v_{fg} = 0.001060 + 0.2 \times (0.89133 - 0.001060) = 0.17911 \text{ m}^3/\text{kg}$$
$$h_1 = h_f + x_1 h_{fg} = 503.81 + 0.2 \times 2202.1 = 944.24 \text{ kJ/kg}$$
$$h_2 = h_{f@120^\circ\text{C}} = 503.81 \text{ kJ/kg}$$

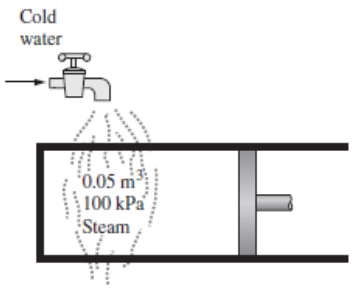
$$m_{steam} = \frac{V_1}{v_1} = \frac{0.01 \text{ m}^3}{0.17911 \text{ m}^3/\text{kg}} = 0.05583 \text{ kg}$$

Noting that $T_{1,ice}$ = 0°C and T_2 = 120°C and substituting gives

$$m[0 + 333.7 \text{ kJ/kg} + (4.18 \text{ kJ/kg·°C})(120\text{-}0)\text{°C}] + (0.05583 \text{ kg})(503.81 - 944.24) \text{ kJ/kg} = 0$$
$$m = 0.0294 \text{ kg} = \mathbf{29.4 \text{ g ice}}$$

4–132 The early steam engines were driven by the atmospheric pressure acting on the piston fitted into a cylinder filled with saturated steam. A vacuum was created in the cylinder by cooling the cylinder externally with cold water, and thus condensing the steam.

Consider a piston–cylinder device with a piston surface area of 0.1 m² initially filled with 0.05 m³ of saturated water vapor at the atmospheric pressure of 100 kPa. Now cold water is poured outside the cylinder, and the steam inside starts condensing as a result of heat transfer to the cooling water outside. If the piston is stuck at its initial position, determine the friction force acting on the piston and the amount of heat transfer when the temperature inside the cylinder drops to 30°C.



4-132 The cylinder of a steam engine initially contains saturated vapor of water at 100 kPa. The cylinder is cooled by pouring cold water outside of it, and some of the steam inside condenses. If the piston is stuck at its initial position, the friction force acting on the piston and the amount of heat transfer are to be determined.

Assumptions The device is air-tight so that no air leaks into the cylinder as the pressure drops.

Analysis We take the contents of the cylinder (the saturated liquid-vapor mixture) as the system, which is a closed system. Noting that the volume remains constant during this phase change process, the energy balance for this system can be expressed as

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

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

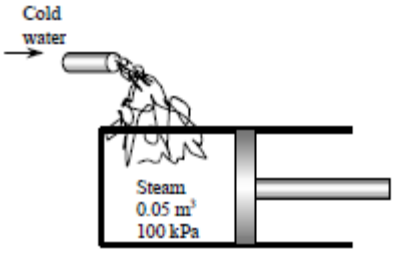
The saturation properties of water at 100 kPa and at 30°C are (Tables A-4 and A-5)

$$P_1 = 100 \text{ kPa} \longrightarrow \begin{array}{ll} v_f = 0.001043 \text{ m}^3/\text{kg}, & v_g = 1.6941 \text{ m}^3/\text{kg} \\ u_f = 417.40 \text{ kJ/kg}, & u_g = 2505.6 \text{ kJ/kg} \end{array}$$

$$T_2 = 30°\text{C} \longrightarrow \begin{array}{ll} v_f = 0.001004 \text{ m}^3/\text{kg}, & v_g = 32.879 \text{ m}^3/\text{kg} \\ u_f = 125.73 \text{ kJ/kg}, & u_{fg} = 2290.2 \text{ kJ/kg} \\ P_{sat} = 4.2469 \text{ kPa} & \end{array}$$

Then,

$$P_2 = P_{sat@30°\text{C}} = 4.2469 \text{ kPa}$$
$$v_1 = v_{g@100\text{ kPa}} = 1.6941 \text{ m}^3/\text{kg}$$
$$u_1 = u_{g@100\text{ kPa}} = 2505.6 \text{ kJ/kg}$$



and

$$m = \frac{V_1}{v_1} = \frac{0.05 \text{ m}^3}{1.6941 \text{ m}^3/\text{kg}} = 0.02951 \text{ kg}$$

$$v_2 = v_1 \longrightarrow x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{1.6941 - 0.001}{32.879 - 0.001} = 0.05150$$

$$u_2 = u_f + x_2 u_{fg} = 125.73 + 0.05150 \times 2290.2 = 243.67 \text{ kJ/kg}$$

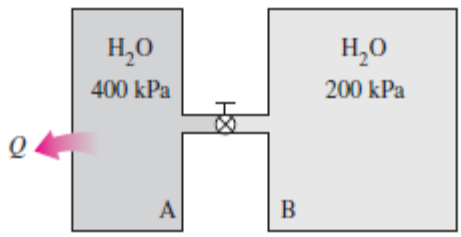
The friction force that develops at the piston-cylinder interface balances the force acting on the piston, and is equal to

$$F = A(P_1 - P_2) = (0.1 \text{ m}^2)(100 - 4.2469)\text{kPa}\left(\frac{1000 \text{ N/m}^2}{1 \text{ kPa}}\right) = \mathbf{9575 \ N}$$

The heat transfer is determined from the energy balance to be

$$\begin{aligned} Q_{out} &= m(u_1 - u_2) \\ &= (0.02951 \text{ kg})(2505.6 - 243.67)\text{kJ/kg} \\ &= \mathbf{66.8 \ kJ} \end{aligned}$$

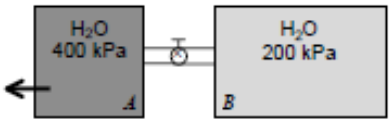
4–134 Two rigid tanks are connected by a valve. Tank A contains 0.2 m³ of water at 400 kPa and 80 percent quality. Tank B contains 0.5 m³ of water at 200 kPa and 250°C. The valve is now opened, and the two tanks eventually come to the same state. Determine the pressure and the amount of heat transfer when the system reaches thermal equilibrium with the surroundings at 25°C. *Answers:* 3.17 kPa, 2170 kJ



4-134 Two rigid tanks that contain water at different states are connected by a valve. The valve is opened and the two tanks come to the same state at the temperature of the surroundings. The final pressure and the amount of heat transfer are to be determined.

Assumptions **1** The tanks are stationary and thus the kinetic and potential energy changes are zero. **2** The tank is insulated and thus heat transfer is negligible. **3** There are no work interactions.

Analysis We take the entire contents of 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



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

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

$$Q_{out} = -[U_{2,A+B} - U_{1,A} - U_{1,B}]$$

$$= -[m_{2,total}u_2 - (m_1u_1)_A - (m_1u_1)_B]$$

The properties of water in each tank are (Tables A-4 through A-6)

Tank A:

$$\left.\begin{array}{l} P_1 = 400 \text{ kPa} \\ x_1 = 0.80 \end{array}\right\} \begin{array}{ll} v_f = 0.001084, & v_g = 0.46242 \text{ m}^3/\text{kg} \\ u_f = 604.22, & u_{fg} = 1948.9 \text{ kJ/kg} \end{array}$$

$$v_{1,A} = v_f + x_1 v_{fg} = 0.001084 + [0.8 \times (0.46242 - 0.001084)] = 0.37015 \text{ m}^3/\text{kg}$$

$$u_{1,A} = u_f + x_1 u_{fg} = 604.22 + (0.8 \times 1948.9) = 2163.3 \text{ kJ/kg}$$

Tank B:

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 250°\text{C} \end{array}\right\} \begin{array}{l} v_{1,B} = 1.1989 \text{ m}^3/\text{kg} \\ u_{1,B} = 2731.4 \text{ kJ/kg} \end{array}$$

$$m_{1,A} = \frac{V_A}{v_{1,A}} = \frac{0.2 \text{ m}^3}{0.37015 \text{ m}^3/\text{kg}} = 0.5403 \text{ kg}$$

$$m_{1,B} = \frac{V_B}{v_{1,B}} = \frac{0.5 \text{ m}^3}{1.1989 \text{ m}^3/\text{kg}} = 0.4170 \text{ kg}$$

$$m_t = m_{1,A} + m_{1,B} = 0.5403 + 0.4170 = 0.9573 \text{ kg}$$

$$v_2 = \frac{V_t}{m_t} = \frac{0.7 \text{ m}^3}{0.9573 \text{ kg}} = 0.73117 \text{ m}^3/\text{kg}$$

$$\left.\begin{array}{l} T_2 = 25°\text{C} \\ v_2 = 0.73117 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{ll} v_f = 0.001003, & v_g = 43.340 \text{ m}^3/\text{kg} \\ u_f = 104.83, & u_{fg} = 2304.3 \text{ kJ/kg} \end{array}$$

Thus at the final state the system will be a saturated liquid-vapor mixture since $v_f < v_2 < v_g$. Then the final pressure must be

$$P_2 = P_{sat\,@\,25\,°C} = \mathbf{3.17\ kPa}$$

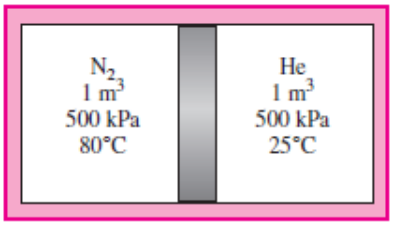
Also,

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.73117 - 0.001}{43.340 - 0.001} = 0.01685$$

$$u_2 = u_f + x_2 u_{fg} = 104.83 + (0.01685 \times 2304.3) = 143.65 \text{ kJ/kg}$$

Substituting, $Q_{out} = -[(0.9573)(143.65) - (0.5403)(2163.3) - (0.4170)(2731.4)] = \mathbf{2170\ kJ}$

4–138 Consider a well-insulated horizontal rigid cylinder that is divided into two compartments by a piston that is free to move but does not allow either gas to leak into the other side. Initially, one side of the piston contains 1 m^3 of N_2 gas at 500 kPa and 80°C while the other side contains 1 m^3 of He gas at 500 kPa and 25°C. Now thermal equilibrium is established in the cylinder as a result of heat transfer through the piston. Using constant specific heats at room temperature, determine the final equilibrium temperature in the cylinder. What would your answer be if the piston were not free to move?

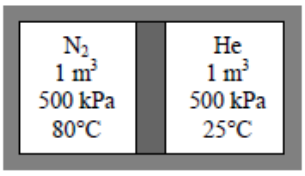


4-138 An insulated cylinder is divided into two parts. One side of the cylinder contains N_2 gas and the other side contains He gas at different states. The final equilibrium temperature in the cylinder when thermal equilibrium is established is to be determined for the cases of the piston being fixed and moving freely.

Assumptions **1** Both N_2 and He are ideal gases with constant specific heats. **2** The energy stored in the container itself is negligible. **3** The cylinder is well-insulated and thus heat transfer is negligible.

Properties The gas constants and the constant volume specific heats are R = 0.2968 kPa.m^3/kg.K is c_v = 0.743 kJ/kg·°C for N_2, and R = 2.0769 kPa.m^3/kg.K is c_v = 3.1156 kJ/kg·°C for He (Tables A-1 and A-2)

Analysis The mass of each gas in the cylinder is



$$m_{N_2} = \left(\frac{P_1V_1}{RT_1}\right)_{N_2} = \frac{(500\text{ kPa})(1\text{ m}^3)}{(0.2968\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(353\text{ K})} = 4.77\text{ kg}$$

$$m_{He} = \left(\frac{P_1V_1}{RT_1}\right)_{He} = \frac{(500\text{ kPa})(1\text{ m}^3)}{(2.0769\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{ K})} = 0.808\text{ kg}$$

Taking the entire contents of the cylinder as our system, the 1st law relation can be written as

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

$$0 = \Delta U = (\Delta U)_{N_2} + (\Delta U)_{He}$$

$$0 = [mc_v(T_2 - T_1)]_{N_2} + [mc_v(T_2 - T_1)]_{He}$$

Substituting,

$$(4.77\text{ kg})(0.743\text{ kJ/kg}\cdot^\circ\text{C})(T_f - 80)^\circ\text{C} + (0.808\text{ kg})(3.1156\text{ kJ/kg}\cdot^\circ\text{C})(T_f - 25)^\circ\text{C} = 0$$

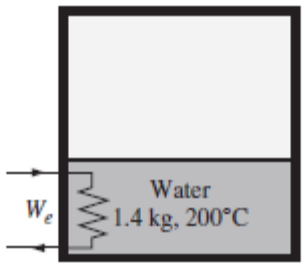
It gives T_f = **57.2°C**

where T_f is the final equilibrium temperature in the cylinder.

The answer would be the **same** if the piston were not free to move since it would effect only pressure, and not the specific heats.

Discussion Using the relation $PV = NR_uT$, it can be shown that the total number of moles in the cylinder is 0.170 + 0.202 = 0.372 kmol, and the final pressure is 510.6 kPa.

4–141 An insulated rigid tank initially contains 1.4-kg saturated liquid water and water vapor at 200°C. At this state, 25 percent of the volume is occupied by liquid water and the rest by vapor. Now an electric resistor placed in the tank is turned on, and the tank is observed to contain saturated water vapor after 20 min. Determine (*a*) the volume of the tank, (*b*) the final temperature, and (*c*) the electric power rating of the resistor. *Answers:* (*a*) 0.00648 m³, (*b*) 371°C, (*c*) 1.58 kW



4-141 An insulated rigid tank initially contains saturated liquid water and air. An electric resistor placed in the tank is turned on until the tank contains saturated water vapor. The volume of the tank, the final temperature, and the power rating of the resistor 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.

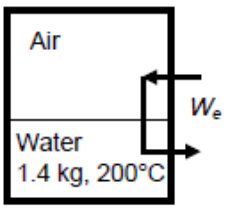
Properties The initial properties of steam are (Table A-4)

$$\left.\begin{array}{l} T_1 = 200°\text{C} \\ x_1 = 0 \end{array}\right\} \begin{array}{l} v_1 = 0.001157\ \text{m}^3/\text{kg} \\ u_1 = 850.46\ \text{kJ/kg} \end{array}$$

Analysis (*a*) We take the contents of 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

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

$$W_{e,in} = \Delta U = m(u_2 - u_1) \quad (\text{since } Q = \text{KE} = \text{PE} = 0)$$



The initial water volume and the tank volume are

$$V_1 = mv_1 = (1.4\ \text{kg})(0.001157\ \text{m}^3/\text{kg}) = 0.001619\ \text{m}^3$$

$$V_{tank} = \frac{0.001619\ \text{m}^3}{0.25} = \mathbf{0.006476\ m^3}$$

(*b*) Now, the final state can be fixed by calculating specific volume

$$v_2 = \frac{V_2}{m} = \frac{0.006476\ \text{m}^3}{1.4\ \text{kg}} = 0.004626\ \text{m}^3/\text{kg}$$

The final state properties are

$$\left.\begin{array}{l} v_2 = 0.004626\ \text{m}^3/\text{kg} \\ x_2 = 1 \end{array}\right\} \begin{array}{l} T_2 = \mathbf{371.3°C} \\ u_2 = 2201.5\ \text{kJ/kg} \end{array}$$

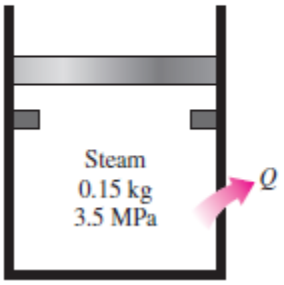
(*c*) Substituting,

$$W_{e,in} = (1.4\ \text{kg})(2201.5 - 850.46)\text{kJ/kg} = 1892\ \text{kJ}$$

Finally, the power rating of the resistor is

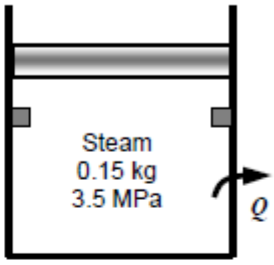
$$\dot{W}_{e,in} = \frac{W_{e,in}}{\Delta t} = \frac{1892\ \text{kJ}}{20 \times 60\ \text{s}} = \mathbf{1.576\ kW}$$

4–143 A piston–cylinder device initially contains 0.15-kg steam at 3.5 MPa, superheated by 5°C. Now the steam loses heat to the surroundings and the piston moves down, hitting a set of stops at which point the cylinder contains saturated liquid water. The cooling continues until the cylinder contains water at 200°C. Determine (*a*) the final pressure and the quality (if mixture), (*b*) the boundary work, (*c*) the amount of heat transfer when the piston first hits the stops, (*d*) and the total heat transfer.



4-143 A piston-cylinder device with a set of stops contains superheated steam. Heat is lost from the steam. The pressure and quality (if mixture), the boundary work, and the heat transfer until the piston first hits the stops and the total heat transfer are to be determined.

Assumptions **1** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **2** The friction between the piston and the cylinder is negligible.



Analysis (*a*) We take the steam in the cylinder to be the system. This is a closed system since no mass crosses the system boundary. The energy balance for this stationary closed system can be expressed as

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

$$W_{b,in} - Q_{out} = \Delta U \quad (\text{since KE} = \text{PE} = 0)$$

Denoting when piston first hits the stops as state (2) and the final state as (3), the energy balance relations may be written as

$$W_{b,in} - Q_{out,1\text{-}2} = m(u_2 - u_1)$$
$$W_{b,in} - Q_{out,1\text{-}3} = m(u_3 - u_1)$$

The properties of steam at various states are (Tables A-4 through A-6)

$$T_{sat@3.5\,MPa} = 242.56°C$$
$$T_1 = T_1 + \Delta T_{sat} = 242.56 + 5 = 247.56°C$$

$$\left.\begin{array}{l} P_1 = 3.5\,\text{MPa} \\ T_1 = 247.56°C \end{array}\right\} \begin{array}{l} v_1 = 0.05821\ \text{m}^3/\text{kg} \\ u_1 = 2617.3\ \text{kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = P_1 = 3.5\,\text{MPa} \\ x_2 = 0 \end{array}\right\} \begin{array}{l} v_2 = 0.001235\ \text{m}^3/\text{kg} \\ u_2 = 1045.4\ \text{kJ/kg} \end{array}$$

$$\left.\begin{array}{l} v_3 = v_2 = 0.001235\ \text{m}^3/\text{kg} \\ T_3 = 200°C \end{array}\right\} \begin{array}{l} \mathbf{x_3 = 0.00062} \\ \mathbf{P_3 = 1555\ kPa} \\ u_3 = 851.55\ \text{kJ/kg} \end{array}$$

(*b*) Noting that the pressure is constant until the piston hits the stops during which the boundary work is done, it can be determined from its definition as

$$W_{b,in} = mP_1(v_1 - v_2) = (0.15\,\text{kg})(3500\ \text{kPa})(0.05821 - 0.001235)\text{m}^3 = \mathbf{29.91\ kJ}$$

(*c*) Substituting into energy balance relations,

$$Q_{out,1\text{-}2} = 29.91\,\text{kJ} - (0.15\,\text{kg})(1045.4 - 2617.3)\text{kJ/kg} = \mathbf{265.7\ kJ}$$

(*d*) $$Q_{out,1\text{-}3} = 29.91\,\text{kJ} - (0.15\,\text{kg})(851.55 - 2617.3)\text{kJ/kg} = \mathbf{294.8\ kJ}$$