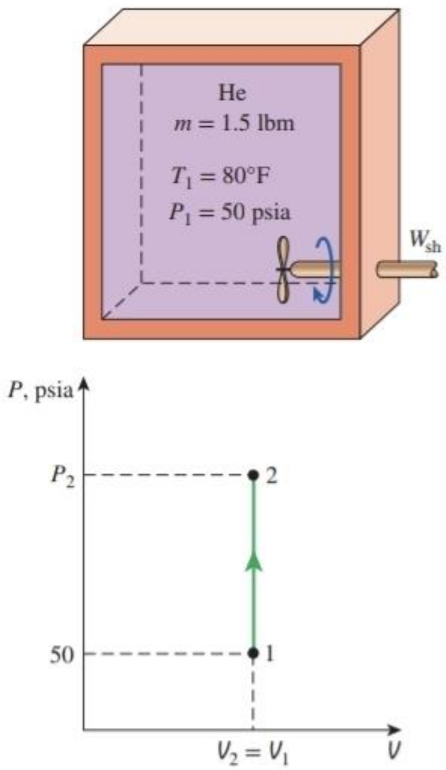


FIGURE 4–30
Schematic and *P*-*V* diagram for Example 4–8.

EXAMPLE 4–8 Heating of a Gas in a Tank by Stirring

An insulated rigid tank initially contains 1.5 lbm of helium at 80°F and 50 psia. A paddle wheel with a power rating of 0.02 hp is operated within the tank for 30 min. Determine (*a*) the final temperature and (*b*) the final pressure of the helium gas.

SOLUTION Helium gas in an insulated rigid tank is stirred by a paddle wheel. The final temperature and pressure of helium are to be determined.

Assumptions **1** Helium is an ideal gas since it is at a very high temperature relative to its critical-point value of −451°F. **2** Constant specific heats can be used for helium. **3** The system is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE = \Delta PE = 0$ and $\Delta E = \Delta U$. **4** The volume of the tank is constant, and thus there is no boundary work. **5** The system is adiabatic and thus there is no heat transfer.

Analysis We take the contents of the tank as the *system* (Fig. 4–30). This is a *closed system* since no mass crosses the system boundary during the process. We observe that there is shaft work done on the system.

(*a*) The amount of paddle-wheel work done on the system is

$$W_{sh} = \dot{W}_{sh}\,\Delta t = (0.02\text{ hp})(0.5\text{ h})\left(\frac{2545\text{ Btu/h}}{1\text{ hp}}\right) = 25.45\text{ Btu}$$

Under the stated assumptions and observations, the energy balance on the system can be expressed as

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

$$W_{sh,in} = \Delta U = m(u_2 - u_1) = mc_{v,avg}(T_2 - T_1)$$

As we pointed out earlier, the ideal-gas specific heats of monatomic gases (helium being one of them) are constant. The c_v value of helium is determined from Table A–2E*a* to be $c_v = 0.753$ Btu/lbm·°F. Substituting this and other known quantities into the preceding equation, we obtain

$$25.45 \text{ Btu} = (1.5 \text{ lbm})(0.753 \text{ Btu/lbm}\cdot°\text{F})(T_2 - 80)°\text{F}$$
$$T_2 = \mathbf{102.5°F}$$

(*b*) The final pressure is determined from the ideal-gas relation

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

where V_1 and V_2 are identical and cancel out. Then the final pressure becomes

$$\frac{50 \text{ psia}}{(80 + 460)\text{R}} = \frac{P_2}{(102.5 + 460)R}$$
$$P_2 = \mathbf{52.1 \text{ psia}}$$

Discussion Note that the pressure in the ideal-gas relation is always the absolute pressure.

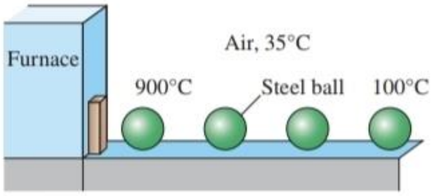


FIGURE 4–36
Schematic for Example 4–13.

EXAMPLE 4–13 Cooling of Carbon Steel Balls in Air

Carbon steel balls ($\rho = 7833$ 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, as shown in Fig. 4-36. If 2500 balls are to be annealed per hour, determine the total rate of heat transfer from the balls to the ambient air.

SOLUTION 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 $\rho = 7833$ 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

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

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

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

The amount of heat transfer from a single ball is

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

$$Q_{\text{out}} = mc(T_1 - T_2) = (0.00210 \text{ kg})(0.465 \text{ kJ/kg·°C})(900 - 100)\text{°C}$$
$$= 0.781 \text{ kJ (per ball)}$$

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

$$\dot{Q}_{\text{out}} = \dot{n}_{\text{ball}}\, Q_{\text{out}} = (2500 \text{ ball/h})(0.781 \text{ kJ/ball}) = 1953 \text{ kJ/h} = \mathbf{542\ W}$$

Discussion For solids and liquids, constant-pressure and constant-volume specific heats are identical and can be represented by a single symbol c. However, it is customary to use the symbol c_p for the specific heat of incompressible substances.

4–19 A piston–cylinder device initially contains 0.4 kg of nitrogen gas at 160 kPa and 140°C. The nitrogen is now expanded isothermally to a pressure of 100 kPa. Determine the boundary work done during this process. *Answer:* 23.0 kJ

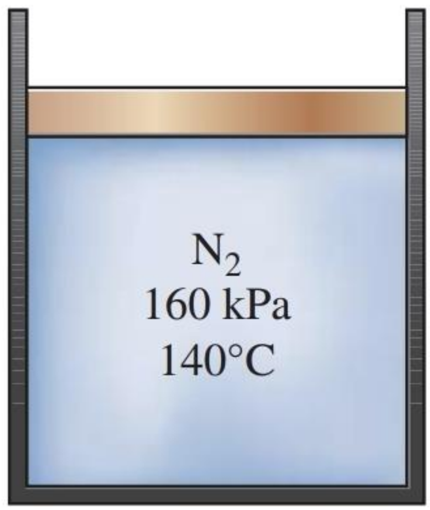


FIGURE P4–19

4-19 A piston-cylinder device contains nitrogen gas at a specified state. The boundary work is to be determined for the isothermal expansion of nitrogen.

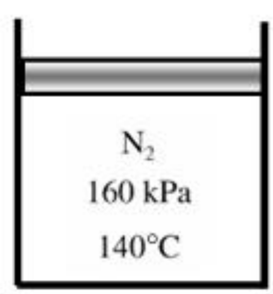
Properties The properties of nitrogen are $R = 0.2968$ kJ/kg.K, $k = 1.4$ (Table A-2a).

Analysis We first determine initial and final volumes from ideal gas relation, and find the boundary work using the relation for isothermal expansion of an ideal gas

$$V_1 = \frac{mRT}{P_1} = \frac{(0.4 \text{ kg})(0.2968 \text{ kJ/kg.K})(140+273 \text{ K})}{160 \text{ kPa}} = 0.3064 \text{ m}^3$$

$$V_2 = \frac{mRT}{P_2} = \frac{(0.4 \text{ kg})(0.2968 \text{ kJ/kg.K})(140+273 \text{ K})}{100 \text{ kPa}} = 0.4903 \text{ m}^3$$

$$W_b = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = (160 \text{ kPa})(0.3064 \text{ m}^3)\ln\left(\frac{0.4903 \text{ m}^3}{0.3064 \text{ m}^3}\right) = \mathbf{23.0 \text{ kJ}}$$

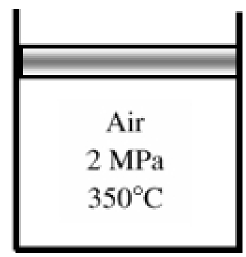


4–20 A piston–cylinder device contains 0.15 kg of air initially at 2 MPa and 350°C. The air is first expanded isothermally to 500 kPa, then compressed polytropically with a polytropic exponent of 1.2 to the initial pressure, and finally compressed at the constant pressure to the initial state. Determine the boundary work for each process and the net work of the cycle.

4-20 A piston-cylinder device contains air gas at a specified state. The air undergoes a cycle with three processes. The boundary work for each process and the net work of the cycle are to be determined.

Properties The properties of air are $R = 0.287$ kJ/kg.K, $k = 1.4$ (Table A-2a).

Analysis For the isothermal expansion process:



$$V_1 = \frac{mRT}{P_1} = \frac{(0.15\text{ kg})(0.287\text{ kJ/kg.K})(350+273\text{ K})}{(2000\text{ kPa})} = 0.01341\text{ m}^3$$

$$V_2 = \frac{mRT}{P_2} = \frac{(0.15\text{ kg})(0.287\text{ kJ/kg.K})(350+273\text{ K})}{(500\text{ kPa})} = 0.05364\text{ m}^3$$

$$W_{b,1-2} = P_1V_1\ln\left(\frac{V_2}{V_1}\right) = (2000\text{ kPa})(0.01341\text{ m}^3)\ln\left(\frac{0.05364\text{ m}^3}{0.01341\text{ m}^3}\right) = \mathbf{37.18\text{ kJ}}$$

For the polytropic compression process:

$$P_2V_2^n = P_3V_3^n \longrightarrow (500\text{ kPa})(0.05364\text{ m}^3)^{1.2} = (2000\text{ kPa})\,V_3^{1.2} \longrightarrow V_3 = 0.01690\text{ m}^3$$

$$W_{b,2-3} = \frac{P_3V_3 - P_2V_2}{1-n} = \frac{(2000\text{ kPa})(0.01690\text{ m}^3) - (500\text{ kPa})(0.05364\text{ m}^3)}{1-1.2} = \mathbf{-34.86\text{ kJ}}$$

For the constant pressure compression process:

$$W_{b,3-1} = P_3(V_1 - V_3) = (2000\text{ kPa})(0.01341-0.01690)\text{m}^3 = \mathbf{-6.97\text{ kJ}}$$

The net work for the cycle is the sum of the works for each process

$$W_{net} = W_{b,1-2} + W_{b,2-3} + W_{b,3-1} = 37.18 + (-34.86) + (-6.97) = \mathbf{-4.65\text{ kJ}}$$

4–22 1 kg of water that is initially at 90°C with a quality of 10 percent occupies a spring-loaded piston–cylinder device, such as that in Fig. P4–22. This device is now heated until the pressure rises to 800 kPa and the temperature is 250°C. Determine the total work produced during this process, in kJ. *Answer:* 24.5 kJ

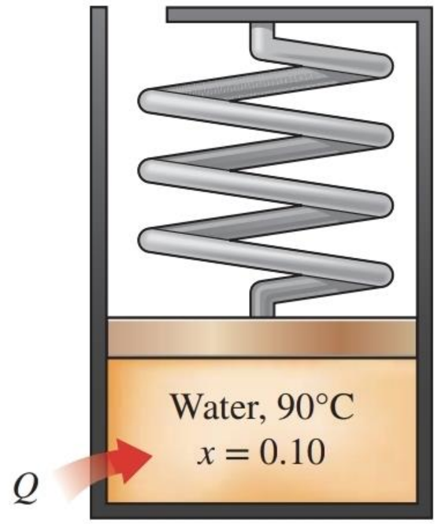
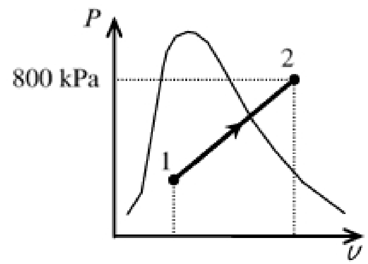


FIGURE P4–22

4-22 A saturated water mixture contained in a spring-loaded piston-cylinder device is heated until the pressure and temperature rises to specified values. The work done during this process is to be determined.

Assumptions The process is quasi-equilibrium.

Analysis The initial state is saturated mixture at 90°C. The pressure and the specific volume at this state are (Table A-4),



$$P_1 = 70.183 \text{ kPa}$$

$$v_1 = v_f + x v_{fg}$$
$$= 0.001036 + (0.10)(2.3593 - 0.001036)$$
$$= 0.23686 \text{ m}^3/\text{kg}$$

The final specific volume at 800 kPa and 250°C is (Table A-6)

$$v_2 = 0.29321 \text{ m}^3/\text{kg}$$

Since this is a linear process, the work done is equal to the area under the process line 1-2:

$$W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2} m(v_2 - v_1)$$
$$= \frac{(70.183 + 800)\text{kPa}}{2}(1 \text{ kg})(0.29321 - 0.23686)\text{m}^3 \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right)$$
$$= \mathbf{24.52 \text{ kJ}}$$

4–24 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

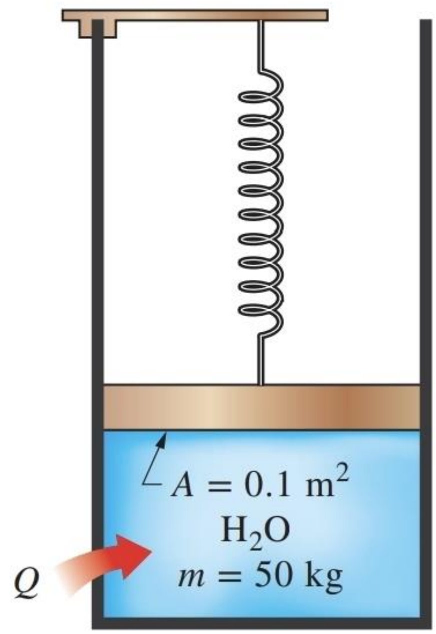


FIGURE P4–24

4-24 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

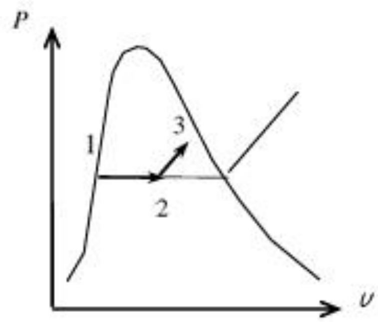
$$\left.\begin{array}{l} T_1 = 25°\text{C} \\ P_1 = 250 \text{ kPa} \end{array}\right\} v_1 \cong v_{f@25°\text{C}} = 0.001003 \text{ m}^3/\text{kg}$$

$$V_1 = m v_1 = (50 \text{ kg})(0.001003 \text{ m}^3/\text{kg}) = 0.05 \text{ m}^3$$

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

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

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



At 450 kPa, v_f = 0.001088 m³/kg and v_g = 0.41392 m³/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,

$$\begin{aligned} W_{b,\text{out}} &= \text{Area} = P_1(V_2 - V_1) + \frac{P_2 + P_3}{2}(V_3 - V_2) \\ &= \left((250 \text{ kPa})(0.2 - 0.05)\text{m}^3 + \frac{(250 + 450) \text{ kPa}}{2}(0.22 - 0.2)\text{m}^3\right)\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) \\ &= \mathbf{44.5\ kJ} \end{aligned}$$

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

4–39 A 40-L electrical radiator containing heating oil is placed in a 50-m^3 room. Both the room and the oil in the radiator are initially at 10°C. The radiator with a rating of 2.4 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/m^3 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.

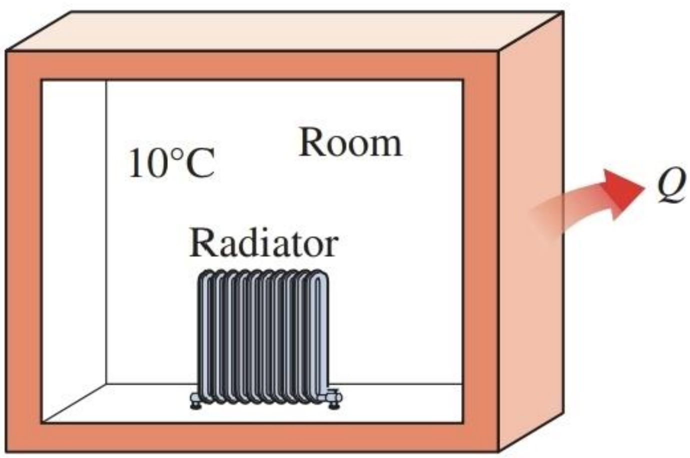


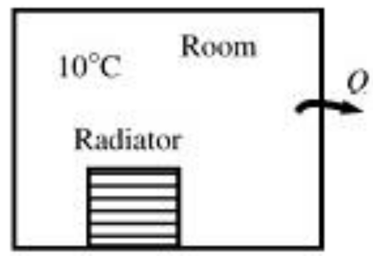
FIGURE P4–39

4-39 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.m^3/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 ρ = 950 kg/m^3 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



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

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

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

The mass of air and oil are

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

$$m_{oil} = \rho_{oil}V_{oil} = (950 \text{ kg/m}^3)(0.040 \text{ m}^3) = 38 \text{ kg}$$

Substituting,

$$(2.4 - 0.35 \text{ kJ/s})\Delta t = (62.32 \text{ kg})(0.718 \text{ kJ/kg}\cdot{}^\circ\text{C})(20 - 10)^\circ\text{C} + (38 \text{ kg})(2.2 \text{ kJ/kg}\cdot{}^\circ\text{C})(50 - 10)^\circ\text{C}$$

$$\longrightarrow \Delta t = \mathbf{1850\ s = 30.8\ min}$$

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.

4–40 Steam at 75 kPa and 8 percent quality is contained in a spring-loaded piston–cylinder device, as shown in Fig. P4–40, with an initial volume of 2 m^3. Steam is now heated until its volume is 5 m^3 and its pressure is 225 kPa. Determine the heat transferred to and the work produced by the steam during this process.

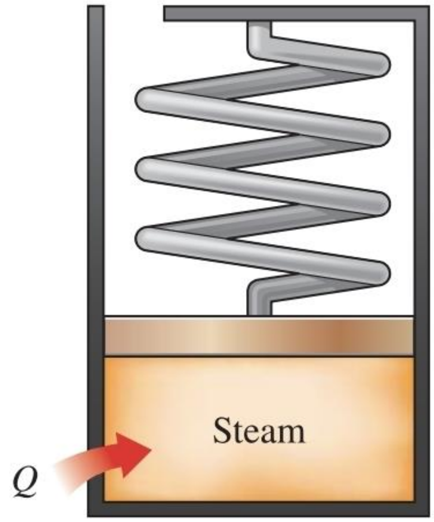


FIGURE P4–40

4-40 A saturated water mixture contained in a spring-loaded piston-cylinder device is heated until the pressure and volume rise to specified values. The heat transfer and the work done are to be determined.

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

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

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

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

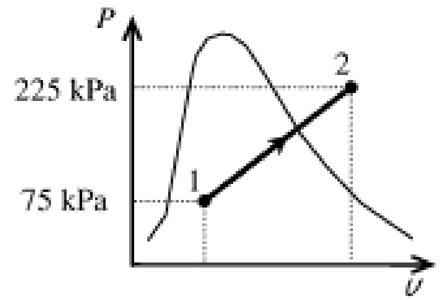
The initial state is saturated mixture at 75 kPa. The specific volume and internal energy at this state are (Table A-5),

$$\upsilon_1 = \upsilon_f + x\upsilon_{fg} = 0.001037 + (0.08)(2.2172 - 0.001037) = 0.1783 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + xu_{fg} = 384.36 + (0.08)(2111.8) = 553.30 \text{ kJ/kg}$$

The mass of water is

$$m = \frac{\mathcal{V}_1}{\upsilon_1} = \frac{2 \text{ m}^3}{0.1783 \text{ m}^3/\text{kg}} = 11.22 \text{ kg}$$



The final specific volume is

$$\upsilon_2 = \frac{\mathcal{V}_2}{m} = \frac{5 \text{ m}^3}{11.22 \text{ kg}} = 0.4458 \text{ m}^3/\text{kg}$$

The final state is now fixed. The internal energy at this specific volume and 225 kPa pressure is (Table A-6)

$$u_2 = 1650.4 \text{ kJ/kg}$$

Since this is a linear process, the work done is equal to the area under the process line 1-2:

$$W_{b,out} = \text{Area} = \frac{P_1 + P_2}{2}(\mathcal{V}_2 - \mathcal{V}_1) = \frac{(75 + 225)\text{kPa}}{2}(5 - 2)\text{m}^3 \left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) = \mathbf{450 \text{ kJ}}$$

Substituting into energy balance equation gives

$$Q_{in} = W_{b,out} + m(u_2 - u_1) = 450 \text{ kJ} + (11.22 \text{ kg})(1650.4 - 553.30) \text{ kJ/kg} = \mathbf{12,750 \text{ kJ}}$$

4–41 A piston–cylinder device initially contains 0.6 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*) 180 kJ, (*c*) 910 kJ

4-41 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.

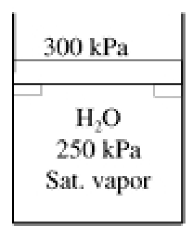
Assumptions **1** The cylinder is stationary and thus the kinetic and potential energy changes are zero. **2** There are no work interactions involved other than the boundary work. **3** The thermal energy stored in the cylinder itself is negligible. **4** The compression or expansion process is quasi-equilibrium.

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

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

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

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



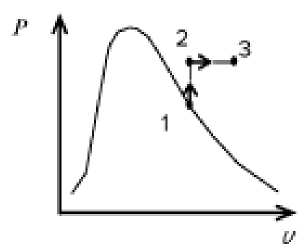
The properties of steam are (Tables A-4 through A-6)

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

$$m = \frac{V_1}{v_1} = \frac{0.6 \text{ m}^3}{0.71873 \text{ m}^3/\text{kg}} = 0.8348 \text{ kg}$$

$$v_3 = \frac{V_3}{m} = \frac{1.2 \text{ m}^3}{0.8348 \text{ kg}} = 1.4375 \text{ m}^3/\text{kg}$$

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



(*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

$$W_{b,\text{out}} = \int_2^3 P\,dV = P(V_3 - V_2) = (300 \text{ kPa})(1.2 - 0.6) \text{ m}^3 \left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right) = \mathbf{180 \text{ kJ}}$$

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

$$\begin{aligned} Q_{\text{in}} &= m(u_3 - u_1) + W_{b,\text{out}} \\ &= (0.8348 \text{ kg})(3411.4 - 2536.8) \text{ kJ/kg} + 180 \text{ kJ} \\ &= \mathbf{910 \text{ kJ}} \end{aligned}$$

4–42 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

4-42 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.

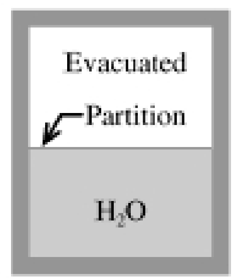
Assumptions **1** The tank is stationary and thus the kinetic and potential energy changes are zero. **2** The tank is insulated and thus heat transfer is negligible. **3** There are no work interactions.

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,

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

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

and,

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

4–44 Two tanks (Tank A and Tank B) are separated by a partition. Initially Tank A contains 2 kg of steam at 1 MPa and 300°C while Tank B contains 3 kg of saturated liquid–vapor mixture at 150°C with a vapor mass fraction of 50 percent. The partition is now removed and the two sides are allowed to mix until 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.

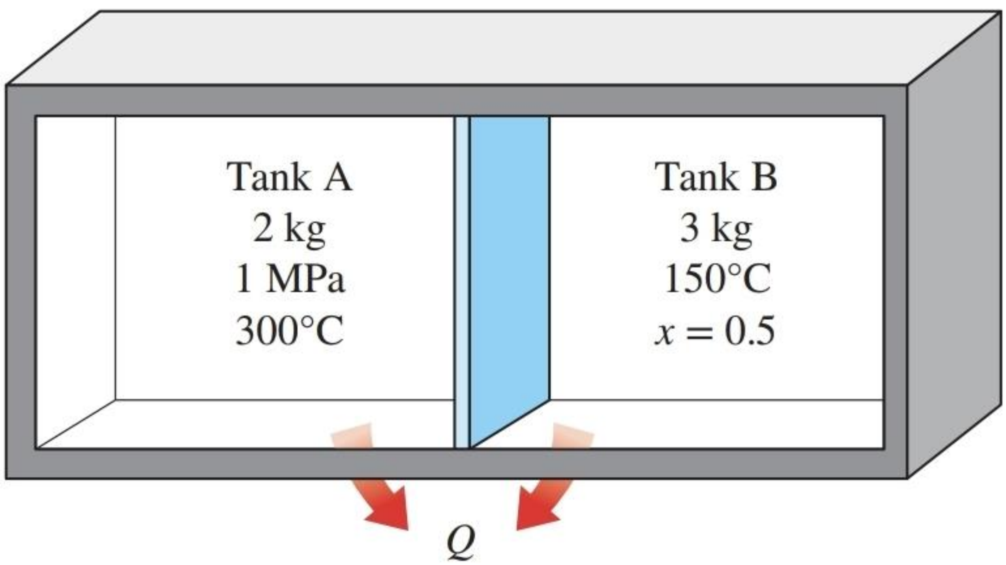
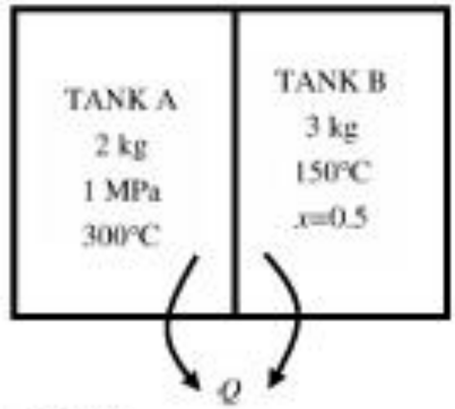


FIGURE P4–44

4-44 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

$$\left.\begin{array}{l} P_2 = 300 \text{ kPa} \\ v_2 = 0.22127 \text{ m}^3/\text{kg} \end{array}\right\} \begin{array}{l} T_2 = T_{sat\,@\,300\,kPa} = \mathbf{133.5°C} \\ x_2 = \dfrac{v_2 - v_f}{v_g - v_f} = \dfrac{0.22127 - 0.001073}{0.60582 - 0.001073} = \mathbf{0.3641} \\ u_2 = u_f + x_2 u_{fg} = 561.11 + (0.3641 \times 1982.1) = 1282.8 \text{ kJ/kg} \end{array}$$

(*b*) Substituting,

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

or

$$Q_{out} = \mathbf{3959\ kJ}$$

4–54 A mass of 10 g of nitrogen is contained in the spring-loaded piston–cylinder device shown in Fig. P4–54. The spring constant is 1 kN/m, and the piston diameter is 10 cm. When the spring exerts no force against the piston, the nitrogen is at 120 kPa and 27°C. The device is now heated until its volume is 10 percent greater than the original volume. Determine the change in the specific internal energy and enthalpy of the nitrogen. *Answers:* 46.8 kJ/kg, 65.5 kJ/kg

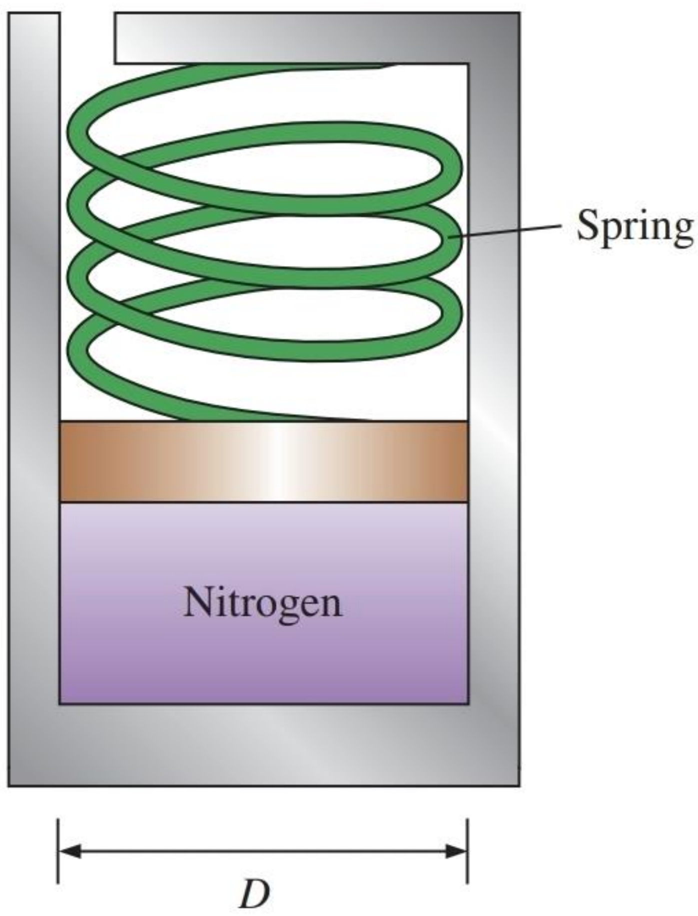


FIGURE P4–54

4-54 A spring-loaded piston-cylinder device is filled with nitrogen. Nitrogen is now heated until its volume increases by 10%. The changes in the internal energy and enthalpy of the nitrogen are to be determined.

Properties The gas constant of nitrogen is $R = 0.2968$ kPa·m³/kg·K. The specific heats of nitrogen at room temperature are $c_v = 0.743$ kJ/kg·K and $c_p = 1.039$ kJ/kg·K (Table A-2a).

Analysis The initial volume of nitrogen is

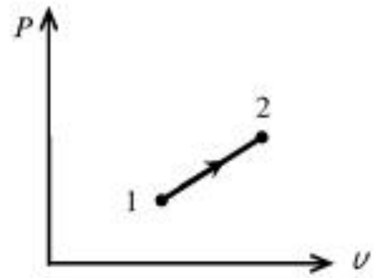
$$V_1 = \frac{mRT_1}{P_1} = \frac{(0.010 \text{ kg})(0.2968 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(27+273 \text{ K})}{120 \text{ kPa}} = 0.00742 \text{ m}^3$$

The process experienced by this system is a linear P-v process. The equation for this line is

$$P - P_1 = c(V - V_1)$$

where P_1 is the system pressure when its specific volume is v_1. The spring equation may be written as

$$P - P_1 = \frac{F_s - F_{s,1}}{A} = k\frac{x - x_1}{A} = \frac{kA}{A^2}(x - x_1) = \frac{k}{A^2}(V - V_1)$$



Constant c is hence

$$c = \frac{k}{A^2} = \frac{4^2 k}{\pi^2 D^4} = \frac{(16)(1 \text{ kN/m})}{\pi^2 (0.1 \text{ m})^4} = 16{,}211 \text{ kN/m}^5$$

The final pressure is then

$$P_2 = P_1 + c(V_2 - V_1) = P_1 + c\left(1.1V_1 - V_1\right) = P_1 + 0.1cV_1$$
$$= 120 \text{ kPa} + 0.1(16{,}211 \text{ kN/m}^5)(0.00742 \text{ m}^3)$$
$$= 132.0 \text{ kPa}$$

The final temperature is

$$T_2 = \frac{P_2V_2}{mR} = \frac{(132.0 \text{ kPa})(1.1\times 0.00742 \text{ m}^3)}{(0.010 \text{ kg})(0.2968 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = 363 \text{ K}$$

Using the specific heats,

$$\Delta u = c_v\Delta T = (0.743 \text{ kJ/kg}\cdot\text{K})(363 - 300)\text{K} = \mathbf{46.8 \text{ kJ/kg}}$$
$$\Delta h = c_p\Delta T = (1.039 \text{ kJ/kg}\cdot\text{K})(363 - 300)\text{K} = \mathbf{65.5 \text{ kJ/kg}}$$

4–69 Argon is compressed in a polytropic process with $n = 1.2$ from 120 kPa and 10°C to 800 kPa in a piston–cylinder device. Determine the work produced and heat transferred during this compression process, in kJ/kg.

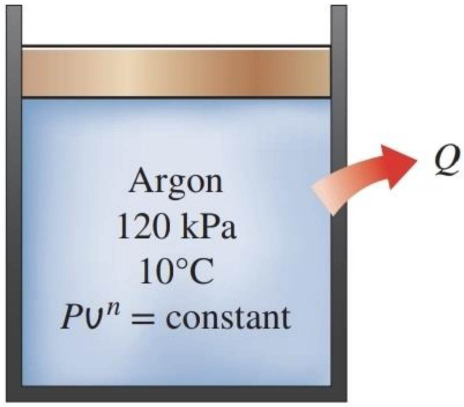


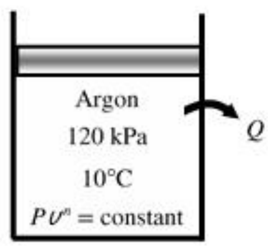
FIGURE P4–69

4-69 Argon is compressed in a polytropic process. The work done and the heat transfer are to be determined.

Assumptions **1** Argon is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of 151 K and 4.86 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$.

Properties The properties of argon are $R = 0.2081$ kJ/kg·K and $c_v = 0.3122$ kJ/kg·K (Table A-2*a*).

Analysis We take argon 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



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

$$Q_{in} - W_{b,out} = \Delta U = mc_v(T_2 - T_1)$$

Using the boundary work relation for the polytropic process of an ideal gas gives

$$w_{b,out} = \frac{RT_1}{1-n}\left[\left(\frac{P_2}{P_1}\right)^{(n-1)/n} - 1\right] = \frac{(0.2081\text{ kJ/kg}\cdot\text{K})(283\text{ K})}{1-1.2}\left[\left(\frac{800}{120}\right)^{0.2/1.2} - 1\right] = -109.5\text{ kJ/kg}$$

Thus,

$$w_{b,in} = \mathbf{109.5\ kJ/kg}$$

The temperature at the final state is

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(n-1)/n} = (283\text{ K})\left(\frac{800\text{ kPa}}{120\text{ kPa}}\right)^{0.2/1.2} = 388.2\text{ K}$$

From the energy balance equation,

$$q_{in} = w_{b,out} + c_v(T_2 - T_1) = -109.5\text{ kJ/kg} + (0.3122\text{ kJ/kg}\cdot\text{K})(388.2 - 283)\text{K} = -76.6\text{ kJ/kg}$$

Thus,

$$q_{out} = \mathbf{76.6\ kJ/kg}$$

4–72 A mass of 15 kg of air in a piston–cylinder device is heated from 25 to 95°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:* 0.310 kWh

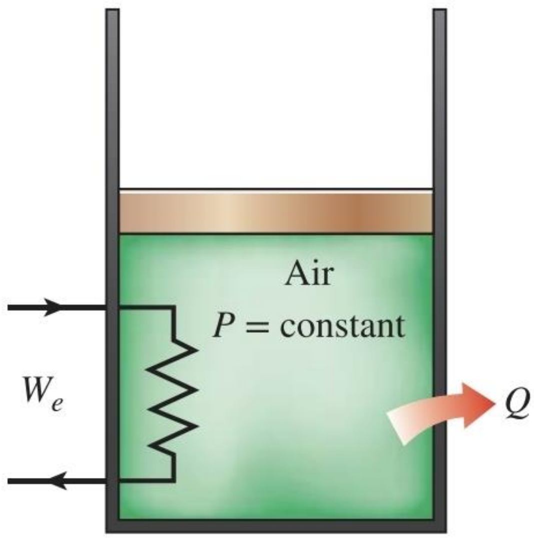


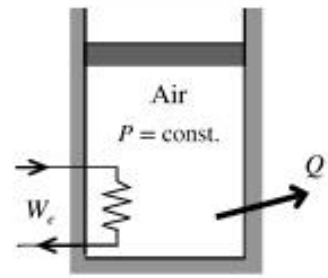
FIGURE P4–72

4-72 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)

$$h_1 = h_{@298\text{ K}} = 298.18 \text{ kJ/kg}$$
$$h_2 = h_{@368\text{ K}} = 368.65 \text{ kJ/kg}$$



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

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

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

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

$$W_{\text{e, in}} = (15 \text{ kg})(368.65 - 298.18)\text{kJ/kg} + (60 \text{ kJ}) = 1117 \text{ kJ}$$

or,

$$W_{e,in} = (1117 \text{ kJ})\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right) = \mathbf{0.310 \text{ kWh}}$$

Alternative solution The specific heat of air at the average temperature of $T_{avg} = (25+ 95)/2 = 60°C = 333$ K is, from Table A-2b, $c_{p,avg} = 1.007$ kJ/kg·°C. Substituting,

$$W_{\text{e,in}} = mc_p(T_2 - T_1) + Q_{\text{out}} = (15 \text{ kg})(1.007 \text{ kJ/kg.°C})(95 - 25)\text{°C} + 60 \text{ kJ} = 1117 \text{ kJ}$$

or,

$$W_{\text{e,in}} = (1117 \text{ kJ})\left(\frac{1 \text{ kWh}}{3600 \text{ kJ}}\right) = \mathbf{0.310 \text{ kWh}}$$

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

4–77 A spring-loaded piston–cylinder device contains 5 kg of helium as the system, as shown in Fig. P4–77. This system is heated from 100 kPa and 20°C to 800 kPa and 160°C. Determine the heat transferred to and the work produced by this system.

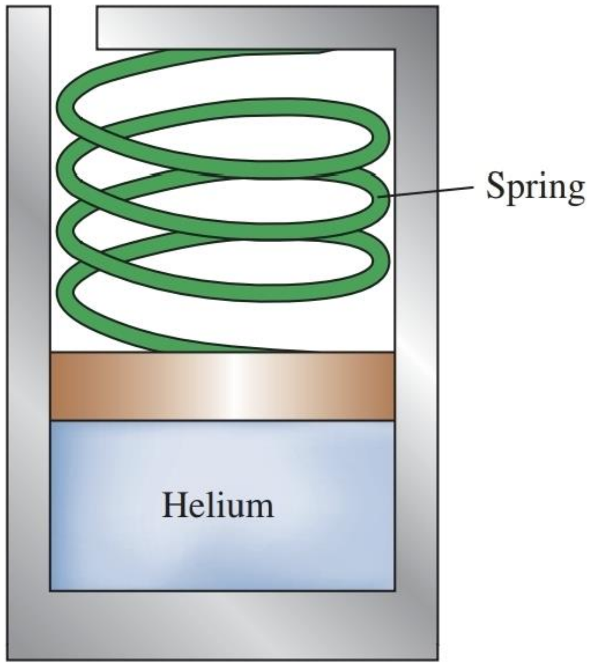


FIGURE P4–77

4-77 Helium contained in a spring-loaded piston-cylinder device is heated. The work done and the heat transfer are to be determined.

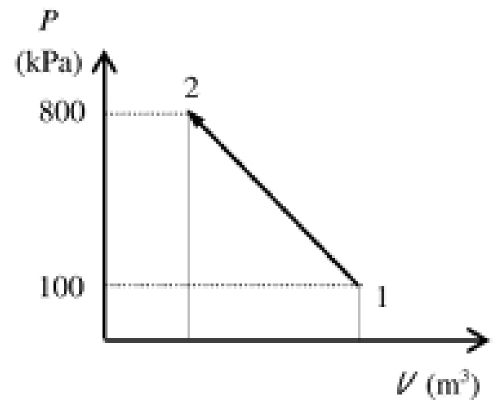
Assumptions **1** Helium is an ideal gas since it is at a high temperature relative to its critical temperature of 5.3 K. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$.

Properties The properties of helium are $R = 2.0769$kJ/kg·K and $c_v = 3.1156$ kJ/kg·K (Table A-2*a*).

Analysis We take helium 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

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

$$Q_{in} - W_{b,out} = \Delta U = mc_v(T_2 - T_1)$$



The initial and final specific volumes are

$$V_1 = \frac{mRT_1}{P_1} = \frac{(5\text{ kg})(2.0769\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\text{ K})}{100\text{ kPa}} = 30.427\text{ m}^3$$

$$V_2 = \frac{mRT_2}{P_2} = \frac{(5\text{ kg})(2.0769\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(160 + 273\text{ K})}{800\text{ kPa}} = 5.621\text{ m}^3$$

Pressure changes linearly with volume and the work done is equal to the area under the process line 1-2:

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

$$= \frac{(100 + 800)\text{kPa}}{2}(5.621 - 30.427)\text{m}^3\left(\frac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right)$$

$$= -11{,}163\text{ kJ}$$

Thus,

$$W_{b,in} = \mathbf{11{,}163\ kJ}$$

Using the energy balance equation,

$$Q_{in} = W_{b,out} + mc_v(T_2 - T_1) = -11{,}163\text{ kJ} + (5\text{ kg})(3.1156\text{ kJ/kg}\cdot\text{K})(160 - 20)\text{K} = -8982\text{ kJ}$$

Thus,

$$Q_{out} = \mathbf{8982\ kJ}$$