5-9 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)
\[
P_1 = 1 \text{ MPa} \quad V_1 = 0.30661 \text{ m}^3/\text{kg} \quad P_2 = 1 \text{ MPa} \quad V_2 = 0.23275 \text{ m}^3/\text{kg}
\]

Noting that pressure is constant during the process, the boundary work is determined from
\[
W_b = mP(V_f - V_i) = (0.3 \text{ kg})(1000 \text{ kPa})(0.30661 - 0.23275) \text{ m}^3/\text{kg} = 22.16 \text{ kJ}
\]

(b) The volume of the cylinder at the final state is 60% of initial volume. Then, the boundary work becomes
\[
W_b = mP(V_f - 0.60V_i) = (0.3 \text{ kg})(1000 \text{ kPa})(0.30661 - 0.60 \times 0.30661) \text{ m}^3/\text{kg} = 36.79 \text{ kJ}
\]

The temperature at the final state is
\[
P_2 = 0.5 \text{ MPa} \quad V_2 = (0.60 \times 0.30661) \text{ m}^3/\text{kg} \quad \Rightarrow T_2 = 151.8^\circ \text{C} \quad \text{(Table A-5)}
\]

5-25 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 \( R = 0.287 \text{ kJ/kg.K} \), \( k = 1.4 \) (Table A-2a).

**Analysis**

For the isothermal expansion process:
\[
V_1 = \frac{mRT_1}{P_1} = \frac{(0.15 \text{ kg})(0.287 \text{ kJ/kg.K})(350 + 273 \text{ K})}{(2000 \text{ kPa})} = 0.01341 \text{ m}^3
\]
\[
V_2 = \frac{mRT_2}{P_2} = \frac{(0.15 \text{ kg})(0.287 \text{ kJ/kg.K})(350 + 273 \text{ K})}{(500 \text{ kPa})} = 0.05364 \text{ m}^3
\]
\[
W_{b,1-2} = P_1 \ln \left( \frac{V_2}{V_1} \right) = (2000 \text{ kPa})(0.01341 \text{ m}^3) \ln \left( \frac{0.05364 \text{ m}^3}{0.01341 \text{ m}^3} \right) = 37.18 \text{ kJ}
\]

For the polytropic compression process:
\[
P_2 V_2^n = P_3 V_3^n \quad \Rightarrow (500 \text{ kPa})(0.05364 \text{ m}^3)^{1.2} = (2000 \text{ kPa})V_3^{1.2} \quad \Rightarrow V_3 = 0.01690 \text{ m}^3
\]
\[
W_{b,2-3} = \frac{P_3 V_3 - P_2 V_2}{1 - n} = \frac{(2000 \text{ kPa})(0.01690 \text{ m}^3) - (500 \text{ kPa})(0.05364 \text{ m}^3)}{1 - 1.2} = -34.86 \text{ kJ}
\]

For the constant pressure compression process:
\[
W_{b,3-1} = P_3 (V_3 - V_1) = (2000 \text{ kPa})(0.01341 - 0.01690) \text{ m}^3 = -6.97 \text{ kJ}
\]

The net work for the cycle is the sum of the works for each process
\[
W_{net} = W_{b,1-2} + W_{b,2-3} + W_{b,3-1} = 37.18 + (-34.86) + (-6.97) = -4.65 \text{ kJ}
\]
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),

\[
P_1 = 70.183 \text{ kPa} \\
\nu_1 = \nu_f + x \nu_{fg} \\
\quad = 0.001036 + (0.10)(2.3593 - 0.001036) \\
\quad = 0.23686 \text{ m}^3/\text{kg}
\]

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

\[
\nu_2 = 0.29321 \text{ m}^3/\text{kg}
\]

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

\[
W_{b,\text{out}} = \text{Area} = \frac{P_1 + P_2}{2} \cdot m(\nu_2 - \nu_1) \\
\quad = \frac{(70.183 + 800)\text{kPa}}{2}(1\text{kg})(0.29321 - 0.23686)\text{m}^3\left(\frac{1\text{kJ}}{1\text{kPa} \cdot \text{m}^3}\right) \\
\quad = 24.52 \text{ kJ}
\]

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-\(\nu\) 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

\[
\frac{\Delta E_{\text{system}}}{\Delta E_{\text{in}}} = \frac{\Delta U}{W_{\text{in}} + W_{\text{pw,\text{in}}}} - W_{\text{b,\text{out}}} = \Delta U \quad \text{(since } Q = KE = PE = 0) \\
W_{\text{e,\text{in}}} + W_{\text{pw,\text{in}}} = m(h_2 - h_1) \\
(\nabla \Delta T) + W_{\text{pw,\text{in}}} = m(h_2 - h_1)
\]

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)
5-65E The air in a rigid tank is heated until its pressure doubles. The volume of the tank and the amount of heat transfer are 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 -221°F and 547 psia.
2. The kinetic and potential energy changes are negligible, \( \Delta p_e \approx \Delta k_e \approx 0 \).
3. Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications.

**Properties**
The gas constant of air is \( R = 0.3704 \text{ psia ft}^3/\text{lbm R} \) (Table A-1E).

**Analysis**
(a) The volume of the tank can be determined from the ideal gas relation,

\[
V = \frac{mRT_1}{P_1} = \frac{(20 \text{ lbm})(0.3704 \text{ psia ft}^3/\text{lbm R})(540 \text{ R})}{50 \text{ psia}} = 80.0 \text{ ft}^3
\]

(b) We take the air in the tank as our system. The energy balance for this stationary closed system can be expressed as

\[
Q_{in} = \Delta U = m(u_2 - u_1) \approx mc_v(T_2 - T_1)
\]

The final temperature of air is

\[
\frac{P_1V}{T_1} = \frac{P_2V}{T_2} \quad \Rightarrow \quad T_2 = \frac{P_2}{P_1}T_1 = 2 \times (540 \text{ R}) = 1080 \text{ R}
\]

The internal energies are (Table A-21E)

\[
u_1 = u_{g(540 R)} = 92.04 \text{ Btu/lbm}
\]

\[
u_2 = u_{g(1080 R)} = 186.93 \text{ Btu/lbm}
\]

Substituting,

\[
Q_{in} = (20 \text{ lbm})(186.93 - 92.04)\text{Btu/lbm} = 1898 \text{ Btu}
\]
**Alternative solutions** The specific heat of air at the average temperature of \( T_{\text{avg}} = \frac{(540+1080)}{2} = 810 \) R = 350°F is, from Table A-2Eb, \( c_{\text{v,avg}} = 0.175 \) Btu/lbm.R. Substituting,
\[
Q_{\text{in}} = (20 \ \text{lbm})(0.175 \ \text{Btu/lbm.R})(1080 - 540) \ R = 1890 \ \text{Btu}
\]

**Discussion** Both approaches resulted in almost the same solution in this case.

5-72 Air in a closed system undergoes an isothermal process. The initial volume, the work done, and the heat transfer are 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 132.5 K and 3.77 MPa. 2 The kinetic and potential energy changes are negligible, \( \Delta ke \equiv \Delta pe \equiv 0 \). 3 Constant specific heats can be used for air.

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

**Analysis** We take the air 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

\[
\frac{E_{\text{in}} - E_{\text{out}}}{Q_{\text{in}} - W_{b,\text{out}}} = \Delta U = mc_{\text{v}}(T_2 - T_1)
\]

The initial volume is
\[
\nu_1 = \frac{mRT_1}{P_1} = \frac{(2 \ \text{kg})(0.287 \ \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(473 \ \text{K})}{600 \ \text{kPa}} = 0.4525 \ \text{m}^3
\]

Using the boundary work relation for the isothermal process of an ideal gas gives
\[
W_{b,\text{out}} = \int_{1}^{2} Pd\nu = mRT \int_{\nu_1}^{\nu_2} \frac{d\nu}{\nu} = mRT \ln \frac{\nu_2}{\nu_1} = mRT \ln \frac{P_1}{P_2}
\]
\[
= (2 \ \text{kg})(0.287 \ \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(473 \ \text{K}) \ln \frac{600 \ \text{kPa}}{80 \ \text{kPa}} = 547.1 \ \text{kJ}
\]

From energy balance equation,
\[
Q_{\text{in}} = W_{b,\text{out}} = 547.1 \ \text{kJ}
\]

5-77 A piston-cylinder device contains air. A paddle wheel supplies a given amount of work to the air. The heat transfer 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 132.5 K and 3.77 MPa. 2 The kinetic and potential energy changes are negligible, \( \Delta ke \equiv \Delta pe \equiv 0 \). 3 Constant specific heats can be used for air.

**Analysis** We take the air 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
Using the boundary work relation on a unit mass basis for the isothermal process of an ideal gas gives

\[ w_{b,\text{out}} = RT \ln \frac{V_2}{V_1} = RT \ln 3 = (0.287 \text{ kJ/kg} \cdot \text{K})(300 \text{ K}) \ln 3 = 94.6 \text{ kJ/kg} \]

Substituting into the energy balance equation (expressed on a unit mass basis) gives

\[ q_{\text{in}} = w_{b,\text{out}} - w_{\text{pw,\text{in}}} = 94.6 - 50 = 44.6 \text{ kJ/kg} \]

**Discussion** Note that the energy content of the system remains constant in this case, and thus the total energy transfer output via boundary work must equal the total energy input via shaft work and heat transfer.

5-84 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, \( \Delta ke \approx \Delta pe = 0 \).
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 \( R = 0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K} \) (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

\[ E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \]

Net energy transfer by heat, work, and mass

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

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

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

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

\[ V_2 = 2V_1 = 2 \times 1.29 = 2.58 \text{ m}^3 \]

\[ \frac{P_1V_1}{T_1} = \frac{P_3V_3}{T_3} \quad \Rightarrow \quad T_3 = \frac{P_3V_3}{P_1V_1}T_1 = 400 \text{ kPa} \times \frac{2 \times (300 \text{ K})}{200 \text{ kPa}} = 1200 \text{ K} \]

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
\[ W_{\text{b,out}} = \int_1^2 P \, dV = P_1 (\mathcal{V}_1 - \mathcal{V}_2) = (400 \text{ kPa})(2.58 - 1.29) \text{m}^3 = 516 \text{ kJ} \]

The initial and final internal energies of air are (Table A-21)
\[
\begin{align*}
  u_1 &= u_{@300 \text{ K}} = 214.07 \text{ kJ/kg} \\
  u_3 &= u_{@1200 \text{ K}} = 933.33 \text{ kJ/kg}
\end{align*}
\]

Then from the energy balance,
\[ Q_{\text{in}} = (3 \text{ kg})(933.33 - 214.07) \text{kJ/kg} + 516 \text{ kJ} = 2674 \text{ kJ} \]

**Alternative solution** The specific heat of air at the average temperature of \( T_{\text{avg}} = (300 + 1200)/2 = 750 \text{ K} \) is, from Table A-2b, \( c_v_{\text{avg}} = 0.800 \text{ kJ/kg.K} \). Substituting,
\[
\begin{align*}
  Q_{\text{in}} &= m(u_3 - u_1) + W_{\text{b,out}} \approx mc_v(T_3 - T_1) + W_{\text{b,out}} \\
  Q_{\text{in}} &= (3 \text{ kg})(0.800 \text{ kJ/kg.K})(1200 - 300) \text{ K} + 516 \text{ kJ} = 2676 \text{ kJ}
\end{align*}
\]