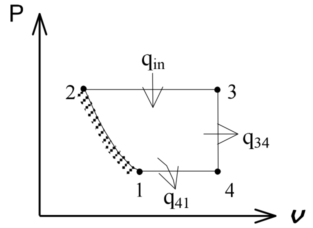
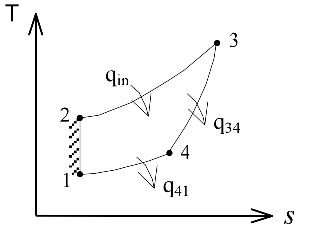
9-16 The four processes of an air-standard cycle are described. The cycle is to be shown on P-υ and T-s diagrams, and the maximum temperature in the cycle and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg.K, c_υ = 0.718 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (*b*) From the ideal gas isentropic relations and energy balance,





$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\ \text{K})\left(\frac{1000\ \text{kPa}}{100\ \text{kPa}}\right)^{0.4/1.4} = 579.2\ \text{K}$$

$$q_{\text{in}} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$2800\ \text{kJ/kg} = (1.005\ \text{kJ/kg}\cdot\text{K})(T_3 - 579.2) \longrightarrow T_{\text{max}} = T_3 = \mathbf{3360\ \ K}$$

(*c*)
$$\frac{P_3\upsilon_3}{T_3} = \frac{P_4\upsilon_4}{T_4} \longrightarrow T_4 = \frac{P_4}{P_3}T_3 = \frac{100\ \text{kPa}}{1000\ \text{kPa}}(3360\ \text{K}) = 336\ \text{K}$$

$$\begin{aligned} q_{\text{out}} &= q_{34,\text{out}} + q_{41,\text{out}} = (u_3 - u_4) + (h_4 - h_1) \\ &= c_\upsilon(T_3 - T_4) + c_p(T_4 - T_1) \\ &= (0.718\ \text{kJ/kg}\cdot\text{K})(3360 - 336)\text{K} + (1.005\ \text{kJ/kg}\cdot\text{K})(336 - 300)\text{K} \\ &= 2212\ \text{kJ/kg} \end{aligned}$$

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{2212\ \text{kJ/kg}}{2800\ \text{kJ/kg}} = \mathbf{21.0\%}$$

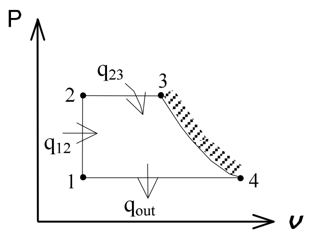
Discussion The assumption of constant specific heats at room temperature is not realistic in this case the temperature changes involved are too large.

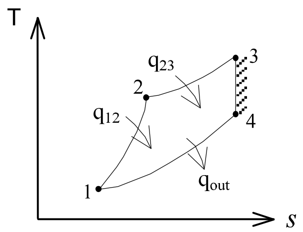
9-17E The four processes of an air-standard cycle are described. The cycle is to be shown on P-υ and T-s diagrams, and the total heat input and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with variable specific heats.

Properties The properties of air are given in Table A-17E.

Analysis (*b*) The properties of air at various states are





$$T_1 = 540\ \text{R} \longrightarrow u_1 = 92.04\ \text{Btu/lbm},\quad h_1 = 129.06\ \text{Btu/lbm}$$

$$q_{\text{in},12} = u_2 - u_1 \longrightarrow \begin{array}{l} u_2 = u_1 + q_{\text{in},12} = 92.04 + 300 = 392.04\ \text{Btu/lbm} \\ T_2 = 2116\text{R},\ h_2 = 537.1\ \text{Btu/lbm} \end{array}$$

$$\frac{P_2\upsilon_2}{T_2} = \frac{P_1\upsilon_1}{T_1} \longrightarrow P_2 = \frac{T_2}{T_1}P_1 = \frac{2116\ \text{R}}{540\ \text{R}}(14.7\ \text{psia}) = 57.6\ \text{psia}$$

$$T_3 = 3200\ \text{R} \longrightarrow \begin{array}{l} h_3 = 849.48\ \text{Btu/lbm} \\ P_{r_3} = 1242 \end{array}$$

$$P_{r_4} = \frac{P_4}{P_3}P_{r_3} = \frac{14.7\ \text{psia}}{57.6\ \text{psia}}(1242) = 317.0 \longrightarrow h_4 = 593.22\ \text{Btu/lbm}$$

From energy balance,

$$q_{23,\text{in}} = h_3 - h_2 = 849.48 - 537.1 = 312.38\ \text{Btu/lbm}$$

$$q_{\text{in}} = q_{12,\text{in}} + q_{23,\text{in}} = 300 + 312.38 = \mathbf{612.38\ Btu/lbm}$$

$$q_{\text{out}} = h_4 - h_1 = 593.22 - 129.06 = 464.16\ \text{Btu/lbm}$$

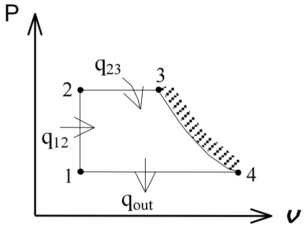
(*c*) Then the thermal efficiency becomes

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{464.16\text{Btu/lbm}}{612.38\text{Btu/lbm}} = \mathbf{24.2\%}$$

9-18E The four processes of an air-standard cycle are described. The cycle is to be shown on *P*-*v* and *T*-*s* diagrams, and the total heat input and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 0.240 Btu/lbm.R, c_v = 0.171 Btu/lbm.R, and k = 1.4 (Table A-2E).



Analysis (*b*)

$$q_{\text{in},12} = u_2 - u_1 = c_v(T_2 - T_1)$$

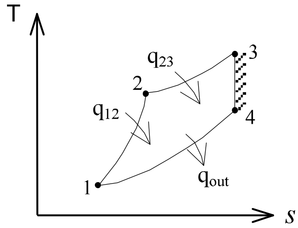
$$300\ \text{Btu/lbm} = (0.171\ \text{Btu/lbm.R})(T_2 - 540)\text{R}$$

$$T_2 = 2294\ \text{R}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{T_2}{T_1}P_1 = \frac{2294\ \text{R}}{540\ \text{R}}(14.7\ \text{psia}) = 62.46\ \text{psia}$$

$$q_{\text{in},23} = h_3 - h_2 = c_p(T_3 - T_2) = (0.24\ \text{Btu/lbm}\cdot\text{R})(3200 - 2294)\text{R} = 217.4\ \text{Btu/lbm}$$

Process 3-4 is isentropic:



$$T_4 = T_3\left(\frac{P_4}{P_3}\right)^{(k-1)/k} = (3200\ \text{R})\left(\frac{14.7\ \text{psia}}{62.46\ \text{psia}}\right)^{0.4/1.4} = 2117\ \text{R}$$

$$q_{\text{in}} = q_{\text{in},12} + q_{\text{in},23} = 300 + 217.4 = \mathbf{517.4\ Btu/lbm}$$

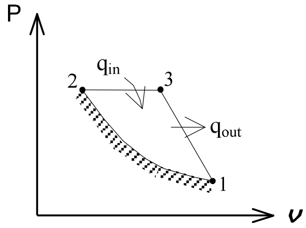
$$q_{\text{out}} = h_4 - h_1 = c_p(T_4 - T_1) = (0.240\ \text{Btu/lbm.R})(2117 - 540) = 378.5\ \text{Btu/lbm}$$

(c) $$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{378.5\ \text{Btu/lbm}}{517.4\ \text{Btu/lbm}} = \mathbf{26.8\%}$$

9-19 The three processes of an air-standard cycle are described. The cycle is to be shown on *P*-*v* and *T*-*s* diagrams, and the heat rejected and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg.K, c_v = 0.718 kJ/kg·K, and k = 1.4 (Table A-2).

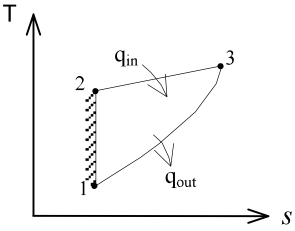


Analysis (*b*) $$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (300\ \text{K})\left(\frac{1000\ \text{kPa}}{100\ \text{kPa}}\right)^{0.4/1.4} = 579.2\ \text{K}$$

$$Q_{\text{in}} = m(h_3 - h_2) = mc_p(T_3 - T_2)$$

$$2.76\ \text{kJ} = (0.004\ \text{kg})(1.005\ \text{kJ/kg}\cdot\text{K})(T_3 - 579.2) \longrightarrow T_3 = 1266\ \text{K}$$

Process 3-1 is a straight line on the *P*-*v* diagram, thus the w_{31} is simply the area under the process curve,



$$w_{31} = \text{area} = \frac{P_3 + P_1}{2}(v_1 - v_3) = \frac{P_3 + P_1}{2}\left(\frac{RT_1}{P_1} - \frac{RT_3}{P_3}\right)$$

$$= \left(\frac{1000 + 100\ \text{kPa}}{2}\right)\left(\frac{300\ \text{K}}{100\ \text{kPa}} - \frac{1266\ \text{K}}{1000\ \text{kPa}}\right)(0.287\ \text{kJ/kg}\cdot\text{K}) = 273.7\ \text{kJ/kg}$$

Energy balance for process 3-1 gives

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \longrightarrow -Q_{31,\text{out}} - W_{31,\text{out}} = m(u_1 - u_3)$$

$$Q_{31,\text{out}} = -mw_{31,\text{out}} - mc_v(T_1 - T_3) = -m\left[w_{31,\text{out}} + c_v(T_1 - T_3)\right]$$

$$= -(0.004\ \text{kg})\left[273.7 + (0.718\ \text{kJ/kg}\cdot\text{K})(300 - 1266)\text{K}\right] = \mathbf{1.679\ kJ}$$

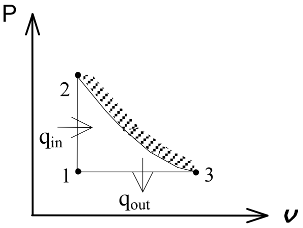
(*c*) $$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{1.679\ \text{kJ}}{2.76\ \text{kJ}} = \mathbf{39.2\%}$$

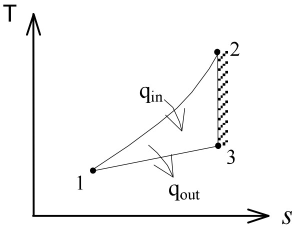
9-20 The three processes of an air-standard cycle are described. The cycle is to be shown on *P*-v and *T*-*s* diagrams, and the net work per cycle and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with variable specific heats.

Properties The properties of air are given in Table A-17.

Analysis (*b*) The properties of air at various states are





$$T_1 = 290\text{ K} \longrightarrow \begin{array}{l} u_1 = 206.91\text{ kJ/kg} \\ h_1 = 290.16\text{ kJ/kg} \end{array}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow T_2 = \frac{P_2}{P_1} T_1 = \frac{380\text{ kPa}}{95\text{ kPa}}(290\text{ K}) = 1160\text{ K}$$

$$\longrightarrow u_2 = 897.91\text{ kJ/kg},\ P_{r_2} = 207.2$$

$$P_{r_3} = \frac{P_3}{P_2} P_{r_2} = \frac{95\text{ kPa}}{380\text{ kPa}}(207.2) = 51.8 \longrightarrow h_3 = 840.38\text{ kJ/kg}$$

$$Q_{\text{in}} = m(u_2 - u_1) = (0.003\text{ kg})(897.91 - 206.91)\text{kJ/kg} = 2.073\text{ kJ}$$

$$Q_{\text{out}} = m(h_3 - h_1) = (0.003\text{ kg})(840.38 - 290.16)\text{kJ/kg} = 1.651\text{ kJ}$$

$$W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}} = 2.073 - 1.651 = \mathbf{0.422\ kJ}$$

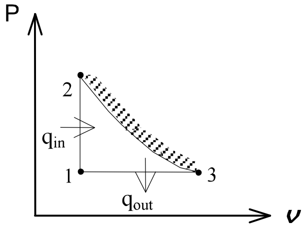
(c) $$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}} = \frac{0.422\text{ kJ}}{2.073\text{ kJ}} = \mathbf{20.4\%}$$

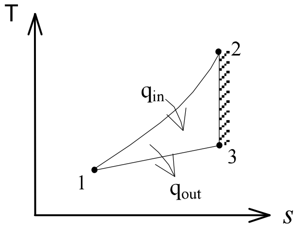
9-21 The three processes of an air-standard cycle are described. The cycle is to be shown on *P*-v and *T*-*s* diagrams, and the net work per cycle and the thermal efficiency are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg.K, c_v = 0.718 kJ/kg·K, and k = 1.4 (Table A-2).

Analysis (*b*) From the isentropic relations and energy balance,





$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow T_2 = \frac{P_2}{P_1} T_1 = \frac{380\text{ kPa}}{95\text{ kPa}}(290\text{ K}) = 1160\text{ K}$$

$$T_3 = T_2 \left(\frac{P_3}{P_2}\right)^{(k-1)/k} = (1160\text{ K})\left(\frac{95\text{ kPa}}{380\text{ kPa}}\right)^{0.4/1.4} = 780.6\text{ K}$$

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

$$= (0.003\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1160 - 290)\text{K} = 1.87\text{ kJ}$$

$$Q_{\text{out}} = m(h_3 - h_1) = mc_p(T_3 - T_1)$$

$$= (0.003\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(780.6 - 290)\text{K} = 1.48\text{ kJ}$$

$$W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}} = 1.87 - 1.48 = \mathbf{0.39\ kJ}$$

(*c*) $$\eta_{\text{th}} = \frac{W_{\text{net}}}{Q_{\text{in}}} = \frac{0.39\text{kJ}}{1.87\text{kJ}} = \mathbf{20.9\%}$$

9-22 A Carnot cycle with the specified temperature limits is considered. The net work output per cycle is to be determined.

Assumptions Air is an ideal gas with constant specific heats.

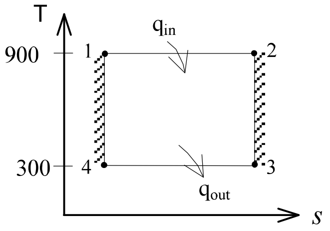
Properties The properties of air at room temperature are c_p = 1.005 kJ/kg.K, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg.K, and $k = 1.4$ (Table A-2).

Analysis The minimum pressure in the cycle is P_3 and the maximum pressure is P_1. Then,

$$\frac{T_2}{T_3} = \left(\frac{P_2}{P_3}\right)^{(k-1)/k}$$

or,

$$P_2 = P_3\left(\frac{T_2}{T_3}\right)^{k/(k-1)} = (20 \text{ kPa})\left(\frac{900 \text{ K}}{300 \text{ K}}\right)^{1.4/0.4} = 935.3 \text{ kPa}$$



The heat input is determined from

$$s_2 - s_1 = \cancelto{0}{c_p \ln\frac{T_2}{T_1}} - R\ln\frac{P_2}{P_1} = -(0.287 \text{ kJ/kg}\cdot\text{K})\ln\frac{935.3 \text{ kPa}}{2000 \text{ kPa}} = 0.2181 \text{ kJ/kg}\cdot\text{K}$$

$$Q_{\text{in}} = mT_H(s_2 - s_1) = (0.003 \text{ kg})(900 \text{ K})(0.2181 \text{ kJ/kg}\cdot\text{K}) = 0.5889 \text{ kJ}$$

Then,

$$\eta_{\text{th}} = 1 - \frac{T_L}{T_H} = 1 - \frac{300 \text{ K}}{900 \text{ K}} = 66.7\%$$

$$W_{\text{net,out}} = \eta_{\text{th}} Q_{\text{in}} = (0.667)(0.5889 \text{ kJ}) = \mathbf{0.393 \ kJ}$$

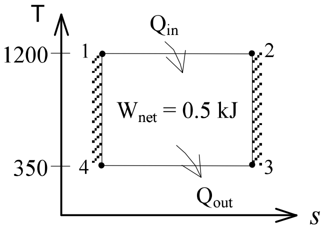
9-23 A Carnot cycle with specified temperature limits is considered. The maximum pressure in the cycle, the heat transfer to the working fluid, and the mass of the working fluid are to be determined.

Assumptions Air is an ideal gas with variable specific heats.

Analysis (*a*) In a Carnot cycle, the maximum pressure occurs at the beginning of the expansion process, which is state 1.

$$\begin{aligned} T_1 &= 1200 \text{ K} &\longrightarrow\quad P_{r_1} &= 238 \\ T_4 &= 350 \text{ K} &\longrightarrow\quad P_{r_4} &= 2.379 \end{aligned} \qquad \text{(Table A-17)}$$

$$P_1 = \frac{P_{r_1}}{P_{r_4}} P_4 = \frac{238}{2.379}(300 \text{ kPa}) = \mathbf{30{,}013 \ kPa} = P_{\max}$$



(*b*) The heat input is determined from

$$\eta_{\text{th}} = 1 - \frac{T_L}{T_H} = 1 - \frac{350 \text{ K}}{1200 \text{ K}} = 70.83\%$$

$$Q_{\text{in}} = W_{\text{net,out}} / \eta_{\text{th}} = (0.5 \text{ kJ})/(0.7083) = \mathbf{0.706 \ kJ}$$

(*c*) The mass of air is

$$s_4 - s_3 = \cancelto{0}{(s_4^\circ - s_3^\circ)} - R\ln\frac{P_4}{P_3} = -(0.287 \text{ kJ/kg}\cdot\text{K})\ln\frac{300 \text{ kPa}}{150 \text{ kPa}}$$

$$= -0.199 \text{ kJ/kg}\cdot\text{K} = s_1 - s_2$$

$$w_{\text{net,out}} = (s_2 - s_1)(T_H - T_L) = (0.199 \text{kJ/kg}\cdot\text{K})(1200 - 350)\text{K} = 169.15 \text{kJ/kg}$$

$$m = \frac{W_{\text{net,out}}}{w_{\text{net,out}}} = \frac{0.5 \text{ kJ}}{169.15 \text{ kJ/kg}} = \mathbf{0.00296 \ kg}$$

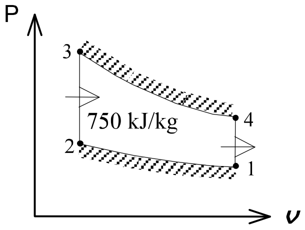
9-34 An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The pressure and temperature at the end of the heat addition process, the net work output, the thermal efficiency, and the mean effective pressure for the cycle are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with variable specific heats.

Properties The gas constant of air is $R = 0.287$ kJ/kg.K. The properties of air are given in Table A-17.

Analysis (*a*) Process 1-2: isentropic compression.

$$T_1 = 300\text{K} \longrightarrow \begin{array}{l} u_1 = 214.07\text{kJ/kg} \\ v_{r_1} = 621.2 \end{array}$$



$$v_{r_2} = \frac{v_2}{v_1} v_{r_1} = \frac{1}{r} v_{r_1} = \frac{1}{8}(621.2) = 77.65 \longrightarrow \begin{array}{l} T_2 = 673.1\,\text{K} \\ u_2 = 491.2\text{ kJ/kg} \end{array}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1} P_1 = (8)\left(\frac{673.1\text{ K}}{300\text{ K}}\right)(95\text{ kPa}) = 1705\text{ kPa}$$

Process 2-3: v = constant heat addition.

$$q_{23,\text{in}} = u_3 - u_2 \longrightarrow u_3 = u_2 + q_{23,\text{in}} = 491.2 + 750 = 1241.2\text{ kJ/kg} \longrightarrow \begin{array}{l} T_3 = \mathbf{1539\ K} \\ v_{r_3} = 6.588 \end{array}$$

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2} P_2 = \left(\frac{1539\text{ K}}{673.1\text{ K}}\right)(1705\text{ kPa}) = \mathbf{3898\ kPa}$$

(*b*) Process 3-4: isentropic expansion.

$$v_{r_4} = \frac{v_1}{v_2} v_{r_3} = r v_{r_3} = (8)(6.588) = 52.70 \longrightarrow \begin{array}{l} T_4 = 774.5\text{ K} \\ u_4 = 571.69\text{ kJ/kg} \end{array}$$

Process 4-1: v = constant heat rejection.

$$q_{\text{out}} = u_4 - u_1 = 571.69 - 214.07 = 357.62\text{ kJ/kg}$$

$$w_{\text{net,out}} = q_{\text{in}} - q_{\text{out}} = 750 - 357.62 = \mathbf{392.4\ kJ/kg}$$

(*c*)
$$\eta_{\text{th}} = \frac{w_{\text{net,out}}}{q_{\text{in}}} = \frac{392.4\text{ kJ/kg}}{750\text{ kJ/kg}} = \mathbf{52.3\%}$$

(*d*)
$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{K})}{95\text{kPa}} = 0.906\text{m}^3/\text{kg} = v_{\max}$$

$$v_{\min} = v_2 = \frac{v_{\max}}{r}$$

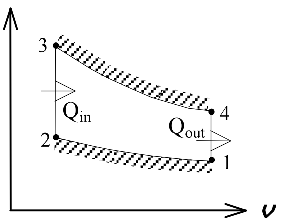
$$\text{MEP} = \frac{w_{\text{net,out}}}{v_1 - v_2} = \frac{w_{\text{net,out}}}{v_1(1-1/r)} = \frac{392.4\text{ kJ/kg}}{(0.906\text{ m}^3/\text{kg})(1-1/8)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{495.0\ kPa}$$

9-37 An ideal Otto cycle with air as the working fluid has a compression ratio of 9.5. The highest pressure and temperature in the cycle, the amount of heat transferred, the thermal efficiency, and the mean effective pressure are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The properties of air at room temperature are c_p = 1.005 kJ/kg·K, c_v = 0.718 kJ/kg·K, R = 0.287 kJ/kg·K, and $k = 1.4$ (Table A-2).

Analysis (*a*) Process 1-2: isentropic compression.



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (308\text{ K})(9.5)^{0.4} = 757.9\text{ K}$$

$$\frac{P_2 v_2}{T_2} = \frac{P_1 v_1}{T_1} \longrightarrow P_2 = \frac{v_1}{v_2}\frac{T_2}{T_1}P_1 = (9.5)\left(\frac{757.9\text{ K}}{308\text{ K}}\right)(100\text{ kPa}) = 2338\text{ kPa}$$

Process 3-4: isentropic expansion.

$$T_3 = T_4\left(\frac{v_4}{v_3}\right)^{k-1} = (800\text{ K})(9.5)^{0.4} = \mathbf{1969\text{ K}}$$

Process 2-3: v = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2}P_2 = \left(\frac{1969\text{ K}}{757.9\text{ K}}\right)(2338\text{ kPa}) = \mathbf{6072\text{ kPa}}$$

(*b*) $$m = \frac{P_1 V_1}{RT_1} = \frac{(100\text{ kPa})(0.0006\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(308\text{ K})} = 6.788\times10^{-4}\text{ kg}$$

$$Q_{\text{in}} = m(u_3 - u_2) = mc_v(T_3 - T_2) = (6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(1969 - 757.9)\text{K} = \mathbf{0.590\text{ kJ}}$$

(c) Process 4-1: v = constant heat rejection.

$$Q_{\text{out}} = m(u_4 - u_1) = mc_v(T_4 - T_1) = -(6.788\times10^{-4}\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(800 - 308)\text{K} = \mathbf{0.240\text{ kJ}}$$

$$W_{\text{net}} = Q_{\text{in}} - Q_{\text{out}} = 0.590 - 0.240 = 0.350\text{ kJ}$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}} = \frac{0.350\text{ kJ}}{0.590\text{ kJ}} = \mathbf{59.4\%}$$

(*d*) $$V_{\min} = V_2 = \frac{V_{\max}}{r}$$

$$\text{MEP} = \frac{W_{\text{net,out}}}{V_1 - V_2} = \frac{W_{\text{net,out}}}{V_1(1-1/r)} = \frac{0.350\text{ kJ}}{(0.0006\text{ m}^3)(1-1/9.5)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{652\text{ kPa}}$$