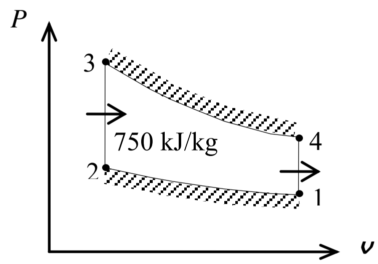
9-33 An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The pressure and temperature at the end of the heat addition process, the net work output, the thermal efficiency, and the mean effective pressure for the cycle are to be determined.

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.

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



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

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

Process 2-3: v = constant heat addition.

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

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

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

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

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

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

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

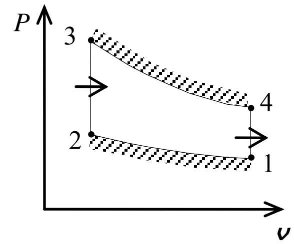
9-36E A six-cylinder, four-stroke, spark-ignition engine operating on the ideal Otto cycle is considered. The power produced by the engine is to be determined.

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 $R = 0.3704$ psia·ft^3/lbm.R (Table A-1E), $c_p = 0.240$ Btu/lbm·R, $c_v = 0.171$ Btu/lbm·R, and $k = 1.4$ (Table A-2Ea).

Analysis From the data specified in the problem statement,

$$r = \frac{v_1}{v_2} = \frac{v_1}{0.098 v_1} = 10.20$$



Since the compression and expansion processes are isentropic,

$$T_2 = T_1 \left(\frac{v_1}{v_2} \right)^{k-1} = T_1 r^{k-1} = (565\text{ R})(10.20)^{1.4-1} = 1430.7\text{ R}$$

$$T_4 = T_3 \left(\frac{v_3}{v_4} \right)^{k-1} = T_3 \left(\frac{1}{r} \right)^{k-1} = (2860\text{ R}) \left(\frac{1}{10.20} \right)^{1.4-1} = 1129.4\text{ R}$$

Application of the first law to the compression and expansion processes gives

$$\begin{aligned} w_{\text{net}} &= c_v (T_3 - T_4) - c_v (T_2 - T_1) \\ &= (0.171\text{ Btu/lbm}\cdot\text{R})(2860 - 1129.4)\text{R} - (0.171\text{ Btu/lbm}\cdot\text{R})(1430.7 - 565)\text{R} \\ &= 147.9\text{ Btu/lbm} \end{aligned}$$

When each cylinder is charged with the air-fuel mixture,

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.3704\text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(565\text{ R})}{14\text{ psia}} = 14.95\text{ ft}^3/\text{lbm}$$

The total air mass taken by all 6 cylinders when they are charged is

$$m = N_{\text{cyl}} \frac{\Delta V}{v_1} = N_{\text{cyl}} \frac{\pi B^2 S / 4}{v_1} = (6) \frac{\pi (3.5/12\text{ ft})^2 (3.9/12\text{ ft})/4}{14.95\text{ ft}^3/\text{lbm}} = 0.008716\text{ lbm}$$

The net work produced per cycle is

$$W_{\text{net}} = m w_{\text{net}} = (0.008716\text{ lbm})(147.9\text{ Btu/lbm}) = 1.289\text{ Btu/cycle}$$

The power produced is determined from

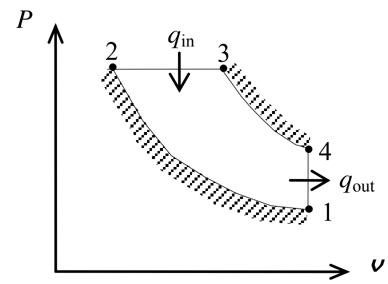
$$\dot{W}_{\text{net}} = \frac{W_{\text{net}} \dot{n}}{N_{\text{rev}}} = \frac{(1.289\text{ Btu/cycle})(2500/60\text{ rev/s})}{2\text{ rev/cycle}} \left(\frac{1\text{ hp}}{0.7068\text{ Btu/s}} \right) = \mathbf{38.0\,hp}$$

since there are two revolutions per cycle in a four-stroke engine.

9-46 An air-standard Diesel cycle with a compression ratio of 16 and a cutoff ratio of 2 is considered. The temperature after the heat addition process, 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 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.

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

$$v_{r_2} = \frac{v_2}{v_1} v_{r_1} = \frac{1}{r} v_{r_1} = \frac{1}{16}(621.2) = 38.825 \longrightarrow \begin{array}{l} T_2 = 862.4\text{ K} \\ h_2 = 890.9\text{ kJ/kg} \end{array}$$

Process 2-3: P = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow T_3 = \frac{v_3}{v_2} T_2 = 2T_2 = (2)(862.4\text{ K}) = \mathbf{1724.8\text{ K}} \longrightarrow \begin{array}{l} h_3 = 1910.6\text{ kJ/kg} \\ v_{r_3} = 4.546 \end{array}$$

(*b*) $$q_{in} = h_3 - h_2 = 1910.6 - 890.9 = 1019.7\text{kJ/kg}$$

Process 3-4: isentropic expansion.

$$v_{r_4} = \frac{v_4}{v_3} v_{r_3} = \frac{v_4}{2v_2} v_{r_3} = \frac{r}{2} v_{r_3} = \frac{16}{2}(4.546) = 36.37 \longrightarrow u_4 = 659.7\text{kJ/kg}$$

Process 4-1: v = constant heat rejection.

$$q_{out} = u_4 - u_1 = 659.7 - 214.07 = 445.63\text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{445.63\text{ kJ/kg}}{1019.7\text{ kJ/kg}} = \mathbf{56.3\%}$$

(*c*) $$w_{net,out} = q_{in} - q_{out} = 1019.7 - 445.63 = 574.07\text{ kJ/kg}$$

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

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

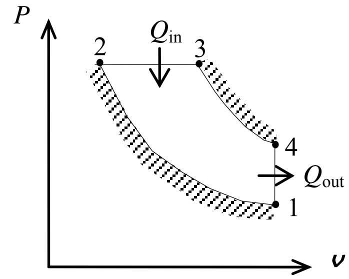
$$\text{MEP} = \frac{w_{net,out}}{v_1 - v_2} = \frac{w_{net,out}}{v_1(1 - 1/r)} = \frac{574.07\text{ kJ/kg}}{(0.906\text{ m}^3/\text{kg})(1 - 1/16)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{675.9\text{ kPa}}$$

9-57 A four-cylinder ideal diesel engine with air as the working fluid has a compression ratio of 22 and a cutoff ratio of 1.8. The power the engine will deliver at 2300 rpm is to be determined.

Assumptions **1** The cold 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 Process 1-2: isentropic compression.



$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (343\text{ K})(22)^{0.4} = 1181\text{ K}$$

Process 2-3: P = constant heat addition.

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow T_3 = \frac{v_3}{v_2}T_2 = 1.8T_2 = (1.8)(1181\text{ K}) = 2126\text{ K}$$

Process 3-4: isentropic expansion.

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = T_3\left(\frac{2.2V_2}{V_4}\right)^{k-1} = T_3\left(\frac{2.2}{r}\right)^{k-1} = (2216\text{ K})\left(\frac{1.8}{22}\right)^{0.4} = 781\text{ K}$$

For the cycle:

$$m = \frac{P_1 V_1}{RT_1} = \frac{(97\text{ kPa})(0.0024\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(343\text{ K})} = 0.002365\text{ kg}$$

$$\begin{aligned} Q_{in} &= m(h_3 - h_2) = mc_p(T_3 - T_2) \\ &= (0.002365\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(2216 - 1181)\text{K} \\ &= 2.246\text{ kJ} \end{aligned}$$

$$\begin{aligned} Q_{out} &= m(u_4 - u_1) = mc_v(T_4 - T_1) \\ &= (0.002365\text{ kg})(0.718\text{ kJ/kg}\cdot\text{K})(781 - 343)\text{K} \\ &= 0.7438\text{ kJ} \end{aligned}$$

$$W_{net,out} = Q_{in} - Q_{out} = 2.246 - 0.7438 = 1.502\text{ kJ/rev}$$

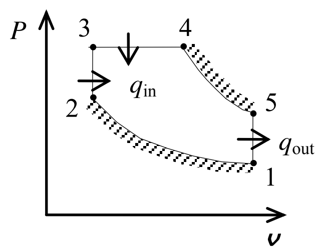
$$\dot{W}_{net,out} = \dot{n}W_{net,out} = (3500/60\text{ rev/s})(1.502\text{ kJ/rev}) = \mathbf{87.6\text{ kW}}$$

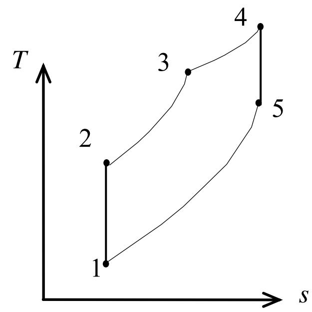
Discussion Note that for 2-stroke engines, 1 thermodynamic cycle is equivalent to 1 mechanical cycle (and thus revolutions).

9-64 The five processes of the dual cycle is described. The *P*-υ and *T*-*s* diagrams for this cycle is to be sketched. An expression for the cycle thermal efficiency is to be obtained and the limit of the efficiency is to be evaluated for certain cases.

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.

Analysis (a) The *P*-υ and *T*-*s* diagrams for this cycle are as shown.





(b) Apply first law to the closed system for processes 2-3, 3-4, and 5-1 to show:

$$q_{in} = C_v\left(T_3 - T_2\right) + C_p\left(T_4 - T_3\right)$$

$$q_{out} = C_v\left(T_5 - T_1\right)$$

The cycle thermal efficiency is given by

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{C_v\left(T_5 - T_1\right)}{C_v\left(T_3 - T_2\right) + C_p\left(T_4 - T_3\right)} = 1 - \frac{T_1\left(T_5/T_1 - 1\right)}{T_2\left(T_3/T_2 - 1\right) + kT_3\left(T_4/T_3 - 1\right)}$$

$$\eta_{th} = 1 - \frac{\left(T_5/T_1 - 1\right)}{\dfrac{T_2}{T_1}\left(T_3/T_2 - 1\right) + k\dfrac{T_3}{T_1}\left(T_4/T_3 - 1\right)}$$

Process 1-2 is isentropic; therefore,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = r^{k-1}$$

Process 2-3 is constant volume; therefore,

$$\frac{T_3}{T_2} = \frac{P_3V_3}{P_2V_2} = \frac{P_3}{P_2} = r_p$$

Process 3-4 is constant pressure; therefore,

$$\frac{P_4V_4}{T_4} = \frac{P_3V_3}{T_3} \Rightarrow \frac{T_4}{T_3} = \frac{V_4}{V_3} = r_c$$

Process 4-5 is isentropic; therefore,

$$\frac{T_5}{T_4} = \left(\frac{V_4}{V_5}\right)^{k-1} = \left(\frac{V_4}{V_1}\right)^{k-1} = \left(\frac{r_cV_3}{V_1}\right)^{k-1} = \left(\frac{r_cV_2}{V_1}\right)^{k-1} = \left(\frac{r_c}{r}\right)^{k-1}$$

Process 5-1 is constant volume; however T_5/T_1 is found from the following.

$$\frac{T_5}{T_1} = \frac{T_5}{T_4}\frac{T_4}{T_3}\frac{T_3}{T_2}\frac{T_2}{T_1} = \left(\frac{r_c}{r}\right)^{k-1} r_c r_p r^{k-1} = r_c^k r_p$$

The ratio T_3/T_1 is found from the following.

$$\frac{T_3}{T_1} = \frac{T_3}{T_2}\frac{T_2}{T_1} = r_p r^{k-1}$$

The efficiency becomes

$$\eta_{th} = 1 - \frac{r_c^k r_p - 1}{r^{k-1}\left(r_p - 1\right) + k r_p r^{k-1}\left(r_c - 1\right)}$$

(c) In the limit as r_p approaches unity, the cycle thermal efficiency becomes

$$\lim_{r_p \to 1} \eta_{th} = 1 - \left\{ \lim_{r_p \to 1} \frac{r_c^k r_p - 1}{r^{k-1}\left(r_p - 1\right) + k r_p r^{k-1}\left(r_c - 1\right)} \right\}$$

$$\lim_{r_p \to 1} \eta_{th} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k\left(r_c - 1\right)}\right] = \eta_{th\ Diesel}$$

(d) In the limit as r_c approaches unity, the cycle thermal efficiency becomes

$$\lim_{r_c \to 1} \eta_{th} = 1 - \left\{ \lim_{r_p \to 1} \frac{r_c^k r_p - 1}{r^{k-1}\left(r_p - 1\right) + k r_p r^{k-1}\left(r_c - 1\right)} \right\} = 1 - \left\{ \frac{r_p - 1}{r^{k-1}\left(r_p - 1\right)} \right\}$$

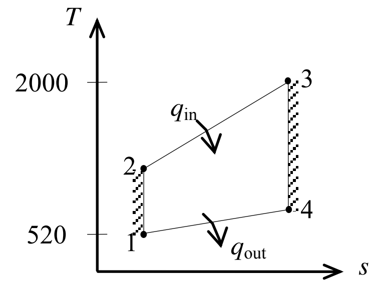
$$\lim_{r_c \to 1} \eta_{th} = 1 - \frac{1}{r^{k-1}} = \eta_{th\ Otto}$$

9-80E A simple ideal Brayton cycle with air as the working fluid has a pressure ratio of 10. The air temperature at the compressor exit, the back work ratio, and the thermal efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** Air is an ideal gas with variable specific heats.

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

Analysis (*a*) Noting that process 1-2 is isentropic,



$$T_1 = 520 \text{ R} \longrightarrow \begin{array}{l} h_1 = 124.27 \text{ Btu/lbm} \\ P_{r_1} = 1.2147 \end{array}$$

$$P_{r_2} = \frac{P_2}{P_1} P_{r_1} = (10)(1.2147) = 12.147 \longrightarrow \begin{array}{l} T_2 = \mathbf{996.5 \text{ R}} \\ h_2 = 240.11 \text{ Btu/lbm} \end{array}$$

(*b*) Process 3-4 is isentropic, and thus

$$T_3 = 2000 \text{ R} \longrightarrow \begin{array}{l} h_3 = 504.71 \text{ Btu/lbm} \\ P_{r_3} = 174.0 \end{array}$$

$$P_{r_4} = \frac{P_4}{P_3} P_{r_3} = \left(\frac{1}{10}\right)(174.0) = 17.4 \longrightarrow h_4 = 265.83 \text{ Btu/lbm}$$

$$w_{\text{C,in}} = h_2 - h_1 = 240.11 - 124.27 = 115.84 \text{ Btu/lbm}$$

$$w_{\text{T,out}} = h_3 - h_4 = 504.71 - 265.83 = 238.88 \text{ Btu/lbm}$$

Then the back-work ratio becomes

$$r_{\text{bw}} = \frac{w_{\text{C,in}}}{w_{\text{T,out}}} = \frac{115.84 \text{ Btu/lbm}}{238.88 \text{ Btu/lbm}} = \mathbf{48.5\%}$$

(*c*) $$q_{\text{in}} = h_3 - h_2 = 504.71 - 240.11 = 264.60 \text{ Btu/lbm}$$

$$w_{\text{net,out}} = w_{\text{T,out}} - w_{\text{C,in}} = 238.88 - 115.84 = 123.04 \text{ Btu/lbm}$$

$$\eta_{\text{th}} = \frac{w_{\text{net,out}}}{q_{\text{in}}} = \frac{123.04 \text{ Btu/lbm}}{264.60 \text{ Btu/lbm}} = \mathbf{46.5\%}$$