HW9

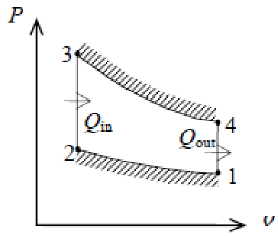
1. (**Problem 9.35 in the book**) The compression ratio of an air-standard Otto cycle is 9.5. Prior to the isentropic compression process, the air is 100 kPa, 35°C, and 600 cm^3. The temperature at the end of the isentropic expansion process is 800 K. Using the specific heat values at room temperature, determine
   a. The highest temperature and pressure in the cycle;
   b. The amount of heat transferred, in kJ;
   c. The thermal efficiency;
   d. The mean effective pressure (MEP).

9-35 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.

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

Process 2-3: v = constant heat addition.

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

(*b*)

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

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

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

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

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

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

(*d*)

$$V_{min} = V_2 = \frac{V_{max}}{r}$$

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

2. (**Problem 9.149 in the book**) An Otto cycle with a compression ratio of 7 begins its operation at 90 kPa and 15°C. The maximum cycle temperature is 1000°C. Utilizing the air-standard assumptions, determine the thermal efficiency using
    a. Constant specific heats at room temperature
    b. Variable specific heats

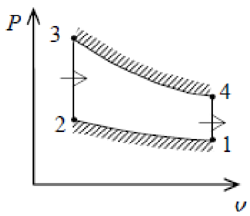
9-149 An Otto cycle with a compression ratio of 7 is considered. The thermal efficiency is to be determined using constant and variable specific heats.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible.

Properties The properties of air at room temperature are $R = 0.287$ kPa·m³/kg·K, $c_p = 1.005$ kJ/kg·K, $c_v = 0.718$ kJ/kg·K, and $k = 1.4$ (Table A-2a).

Analysis (*a*) Constant specific heats:

$$\eta_{\text{th}} = 1 - \frac{1}{r^{k-1}} = 1 - \frac{1}{7^{1.4-1}} = 0.5408 = \mathbf{54.1\%}$$



(b) Variable specific heats: (using air properties from Table A-17)

Process 1-2: isentropic compression.

$$T_1 = 288 \text{ K} \longrightarrow \begin{array}{l} u_1 = 205.48 \text{ kJ/kg} \\ v_{r1} = 688.1 \end{array}$$

$$v_{r2} = \frac{v_2}{v_1} v_{r2} = \frac{1}{r} v_{r2} = \frac{1}{7}(688.1) = 98.3 \longrightarrow u_2 = 447.62 \text{ kJ/kg}$$

Process 2-3: v = constant heat addition.

$$T_3 = 1273 \text{ K} \longrightarrow \begin{array}{l} u_3 = 998.51 \text{ kJ/kg} \\ v_{r3} = 12.045 \end{array}$$

$$q_{in} = u_3 - u_2 = 998.51 - 447.62 = 550.89 \text{ kJ/kg}$$

Process 3-4: isentropic expansion.

$$v_{r4} = \frac{v_4}{v_3} v_{r3} = r v_{r3} = (7)(12.045) = 84.32 \longrightarrow u_4 = 475.54 \text{ kJ/kg}$$

Process 4-1: v = constant heat rejection.

$$q_{\text{out}} = u_4 - u_1 = 475.54 - 205.48 = 270.06 \text{ kJ/kg}$$

$$\eta_{\text{th}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{270.06 \text{ kJ/kg}}{550.89 \text{ kJ/kg}} = 0.5098 = \mathbf{51.0\%}$$

3. (**Problem 9.52 in the book**) An ideal Diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. If the maximum temperature in the cycle is not to exceed 2200 K, determine
    a. The thermal efficiency
    b. The mean effective pressure

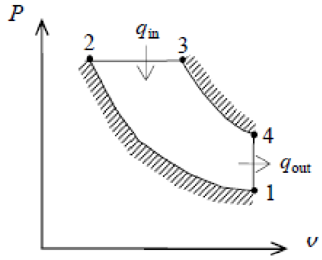
   Assume constant specific heats for air at room temperature. (Answers: (a) 63.5% (b) 933 kPa)

9-52 An ideal diesel engine with air as the working fluid has a compression ratio of 20. 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.



$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (293\text{ K})(20)^{0.4} = 971.1\text{ K}$$

Process 2-3: P = constant heat addition.

$$\frac{P_3V_3}{T_3} = \frac{P_2V_2}{T_2} \longrightarrow \frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{2200\text{K}}{971.1\text{K}} = 2.265$$

Process 3-4: isentropic expansion.

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = T_3\left(\frac{2.265V_2}{V_4}\right)^{k-1} = T_3\left(\frac{2.265}{r}\right)^{k-1} = (2200\text{ K})\left(\frac{2.265}{20}\right)^{0.4} = 920.6\text{ K}$$

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2) = (1.005\text{ kJ/kg}\cdot\text{K})(2200 - 971.1)\text{K} = 1235\text{ kJ/kg}$$

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1) = (0.718\text{ kJ/kg}\cdot\text{K})(920.6 - 293)\text{K} = 450.6\text{ kJ/kg}$$

$$w_{net,out} = q_{in} - q_{out} = 1235 - 450.6 = 784.4\text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{784.4\text{ kJ/kg}}{1235\text{ kJ/kg}} = \mathbf{63.5\%}$$

(*b*) $$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(293\text{ K})}{95\text{ kPa}} = 0.885\text{ m}^3/\text{kg} = v_{max}$$

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

$$\text{MEP} = \frac{w_{net,out}}{v_1 - v_2} = \frac{w_{net,out}}{v_1(1-1/r)} = \frac{784.4\text{ kJ/kg}}{(0.885\text{ m}^3/\text{kg})(1-1/20)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{933\text{ kPa}}$$

4. (**Problem 9.60 in the book**) A six-cylinder, four-stroke, 3.2-L compression ignition engine operates on the ideal Diesel cycle with a compression ratio of 19. The air is at 95 kPa and 67°C at the beginning of the compression process and the engine speed is 1750 rpm. The engine uses light Diesel fuel with a heating value of 42,500 kJ/kg, an air-fuel ratio of 28, and a combustion efficiency of 98%. Using constant specific heats at 850 K, determine
   a. The maximum temperature in the cycle and the cut-off ratio
   b. The net work output per cycle and the thermal efficiency
   c. The mean effective pressure (MEP)
   d. The net power output, and
   e. The specific fuel consumption, in g/kWh, defined as the ratio of the mass of the fuel consumed to the net work output produced.

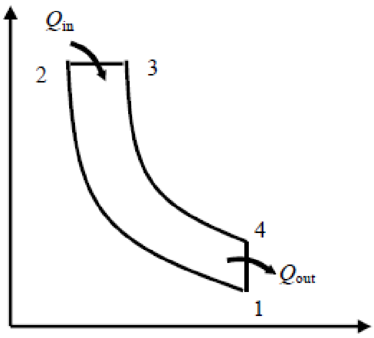
   (Answers: (a) 2244 K, 2.36, (b) 2.71 kJ, 57.4%, (c) 847 kPa, (d) 39.5 kW, (e) 151 g/kWh)

9-60 A six-cylinder compression ignition engine operates on the ideal Diesel cycle. The maximum temperature in the cycle, the cutoff ratio, the net work output per cycle, the thermal efficiency, the mean effective pressure, the net power output, and the specific fuel consumption 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 850 K are c_p = 1.110 kJ/kg·K, c_v = 0.823 kJ/kg·K, R = 0.287 kJ/kg·K, and k = 1.349 (Table A-2b).

Analysis (*a*) Process 1-2: Isentropic compression



$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (340\text{ K})(19)^{1.349\text{-}1} = 950.1\text{ K}$$

$$P_2 = P_1\left(\frac{v_1}{v_2}\right)^{k} = (95\text{ kPa})(19)^{1.349} = 5044\text{ kPa}$$

The clearance volume and the total volume of the engine at the beginning of compression process (state 1) are

$$r = \frac{V_c + V_d}{V_c} \longrightarrow 19 = \frac{V_c + 0.0045\text{ m}^3}{V_c}$$

$$V_c = 0.0001778\text{ m}^3$$

$$V_1 = V_c + V_d = 0.0001778 + 0.0032 = 0.003378\text{ m}^3$$

The total mass contained in the cylinder is

$$m = \frac{P_1 V_1}{RT_1} = \frac{(95\text{ kPa})(0.003378\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(340\text{ K})} = 0.003288\text{ kg}$$

The mass of fuel burned during one cycle is

$$AF = \frac{m_a}{m_f} = \frac{m - m_f}{m_f} \longrightarrow 28 = \frac{(0.003288\text{ kg}) - m_f}{m_f} \longrightarrow m_f = 0.0001134\text{ kg}$$

Process 2-3: constant pressure heat addition

$$Q_{in} = m_f q_{HV}\eta_c = (0.0001134\text{ kg})(42{,}500\text{ kJ/kg})(0.98) = 4.723\text{ kJ}$$

$$Q_{in} = mc_v(T_3 - T_2) \longrightarrow 4.723\text{ kJ} = (0.003288\text{ kg})(0.823\text{kJ/kg.K})(T_3 - 950.1)\text{K} \longrightarrow T_3 = \mathbf{2244\text{ K}}$$

The cutoff ratio is

$$\beta = \frac{T_3}{T_2} = \frac{2244\text{ K}}{950.1\text{ K}} = \mathbf{2.362}$$

(*b*) $$V_2 = \frac{V_1}{r} = \frac{0.003378\text{ m}^3}{19} = 0.0001778\text{ m}^3$$

$$V_3 = \beta V_2 = (2.362)(0.0001778\text{ m}^3) = 0.0004199\text{ m}^3$$

$$V_4 = V_1$$

$$P_3 = P_2$$

Process 3-4: isentropic expansion.

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = (2244\,\text{K})\left(\frac{0.0004199\,\text{m}^3}{0.003378\,\text{m}^3}\right)^{1.349\text{-}1} = 1084\,\text{K}$$

$$P_4 = P_3\left(\frac{V_3}{V_4}\right)^{k} = (5044\,\text{kPa})\left(\frac{0.0004199\,\text{m}^3}{0.003378\,\text{m}^3}\right)^{1.349} = 302.9\,\text{kPa}$$

Process 4-1: constant voume heat rejection.

$$Q_{\text{out}} = mc_v(T_4 - T_1) = (0.003288\,\text{kg})(0.823\,\text{kJ/kg}\cdot\text{K})(1084 - 340)\text{K} = 2.013\,\text{kJ}$$

The net work output and the thermal efficiency are

$$W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}} = 4.723 - 2.013 = \mathbf{2.710\ kJ}$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}} = \frac{2.710\,\text{kJ}}{4.723\,\text{kJ}} = 0.5737 = \mathbf{57.4\%}$$

(*c*) The mean effective pressure is determined to be

$$\text{MEP} = \frac{W_{\text{net,out}}}{V_1 - V_2} = \frac{2.710\,\text{kJ}}{(0.003378 - 0.0001778)\text{m}^3}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{847\ kPa}$$

(*d*) The power for engine speed of 1750 rpm is

$$\dot{W}_{\text{net}} = W_{\text{net}}\frac{\dot{n}}{2} = (2.710\,\text{kJ/cycle})\frac{1750\,(\text{rev/min})}{(2\,\text{rev/cycle})}\left(\frac{1\,\text{min}}{60\,\text{s}}\right) = \mathbf{39.5\ kW}$$

Note that there are two revolutions in one cycle in four-stroke engines.

(*e*) Finally, the specific fuel consumption is

$$\text{sfc} = \frac{m_f}{W_{\text{net}}} = \frac{0.0001134\,\text{kg}}{2.710\,\text{kJ/kg}}\left(\frac{1000\,\text{g}}{1\,\text{kg}}\right)\left(\frac{3600\,\text{kJ}}{1\,\text{kWh}}\right) = \mathbf{151\ g/kWh}$$