Known: An air-standard otto cycle has a known compression ratio and a specified state at the beginning of compression. The heat addition per unit mass of air is given.

Find: Determine (a) the net work per unit mass of air, (b) the thermal efficiency, (c) the mean effective pressure, and (d) the maximum cycle temperature. (e) Plot each of these quantities versus compression ratio.

Schematic & Given Data:

\[ P, \frac{V_i}{V_o} = 8.5 \]
\[ Q_{23} = 1400 \text{ kJ/kg} \]
\[ P_i = 100 \text{ kPa} \]
\[ T_i = 300 \text{ K} \]
\[ V_i = 621.2 \text{ cm}^3 \]

Assumptions: See Example 9.1

Analysis: Begin by fixing each principal state of the cycle (Table A-22).

State 1: \[ p = 100 \text{ kPa}, T_i = 300 \text{ K} \]
\[ u_i = 214.07 \text{ kJ/kg}, v_i = 621.2 \]

State 2: For isentropic compression
\[ \frac{v_n}{v_1} = \frac{4}{5} = 0.8 \]
Thus, \[ T_2 = 688.2 \text{ K}, u_2 = 503.06 \]

State 3: The specific internal energy \( u_3 \) is found using the energy balance for process 2-3
\[ m (u_3 - u_2) = Q_{23} - W_{23} \]
\[ u_3 = \frac{Q_{23}}{m} + u_2 = 1400 \frac{kJ}{kg} + 503.06 \frac{kJ}{kg} = 1903.06 \]
Thus, \[ T_3 = 2281.3 \text{ K}, v_{r3} = 1.1942 \]

State 4: For the isentropic expansion
\[ \frac{u_4}{u_3} = \frac{v_3}{v_4} = \frac{v_3}{v_2} = (1.1942)(0.5) = 0.597 \]
Finally, \[ T_4 = 1154.8 \text{ K}, u_4 = 892.45 \text{ kJ/kg} \]

(a) To find the net work, note that \( W_{cycle} = Q_{23} \), so
\[ \frac{W_{cycle}}{m} = \frac{Q_{23}}{m} = \frac{Q_{23}}{m} - (u_4 - u_1) \]
\[ = 1400 - (892.45 - 214.07) = 721.12 \frac{kJ}{kg} \]

(b) The thermal efficiency is
\[ \eta = \frac{W_{cycle}/m}{Q_{23}/m} = \frac{721.12}{1400} = 0.515 \text{ (51.5\%)} \]

(c) The displacement volume is \( V_r - V_i = m(v_r - v_i) \), so the mean effective pressure is given by
PROBLEM 9.1 (Contd.)

\[
\text{mep} = \frac{\text{W}_{\text{cycle}}}{V_1 - V_2} = \frac{\text{W}_{\text{cycle/m}}}{\tau_1 - \tau_2} = \frac{\text{W}_{\text{cycle/m}}}{\tau_1 (1 - \frac{V_2}{V_1})}
\]

Evaluating \( \tau_1 \):

\[
\tau_1 = \frac{RT_1}{p_1} = \frac{\left(8.314 \text{ kT} / \text{kg-K} \right) (300 \text{ K})}{(100 \text{ kPa})} = 0.861 \text{ m}^3/\text{kg}
\]

Thus:

\[
\text{mep} = \frac{(721.12 \text{ kJ/kg})}{(0.861 \text{ m}^3/\text{kg}) (1 - \frac{1}{8.5})} = 999.2 \text{ kPa}
\]

The data for the required plots are obtained using IT, as follows:

<table>
<thead>
<tr>
<th>IT Code</th>
<th>W_{\text{cycle}} = q_{\text{cycle}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>r = 8.5</td>
<td>W_{\text{cycle}} / m = Q_{23} / m - Q_{41} / m</td>
</tr>
<tr>
<td>P_1 = 100 // kPa</td>
<td>Q_{41}/m = u_4 - u_1</td>
</tr>
<tr>
<td>T_1 = 300 // K</td>
<td>eta = W_{\text{cycle}} / Q_{23}</td>
</tr>
<tr>
<td>Q_{23} / m = 1400 // kJ/kg</td>
<td>V_1 = v_1 * m</td>
</tr>
<tr>
<td>m = 1 // assume a unit mass of 1 kg.</td>
<td>V_2 = v_2 * m</td>
</tr>
<tr>
<td>v_1 = v_{\text{TP}}(&quot;Air&quot;, T_1, p_1)</td>
<td>mep = W_{\text{cycle}} / (V_1 - V_2)</td>
</tr>
<tr>
<td>s_1 = s_{\text{TP}}(&quot;Air&quot;, T_1, p_1)</td>
<td></td>
</tr>
<tr>
<td>u_1 = u_{\text{TP}}(&quot;Air&quot;, T_1)</td>
<td></td>
</tr>
<tr>
<td>s_2 = s_1</td>
<td></td>
</tr>
<tr>
<td>v_2 = v_1 / r</td>
<td></td>
</tr>
<tr>
<td>s_2 = s_{\text{TP}}(&quot;Air&quot;, T_2, p_2)</td>
<td></td>
</tr>
<tr>
<td>v_2 = v_{\text{TP}}(&quot;Air&quot;, T_2, p_2)</td>
<td></td>
</tr>
<tr>
<td>u_2 = u_{\text{TP}}(&quot;Air&quot;, T_2)</td>
<td></td>
</tr>
<tr>
<td>v_3 = v_2</td>
<td></td>
</tr>
<tr>
<td>m * (u_3 - u_2) = Q_{23} - W_{23}</td>
<td></td>
</tr>
<tr>
<td>W_{23} = 0</td>
<td></td>
</tr>
<tr>
<td>u_3 = u_{\text{TP}}(&quot;Air&quot;, T_3)</td>
<td>IT Results for r = 0.85</td>
</tr>
<tr>
<td>v_3 = v_{\text{TP}}(&quot;Air&quot;, T_3, p_3)</td>
<td>Q_4 / m = 678.8 kJ/kg</td>
</tr>
<tr>
<td>s_3 = s_{\text{TP}}(&quot;Air&quot;, T_3, p_3)</td>
<td>T_4 = 1155 K</td>
</tr>
<tr>
<td>v_4 = r * v_3</td>
<td>u_1 = 213.9 kJ/kg</td>
</tr>
<tr>
<td>s_4 = s_3</td>
<td>u_2 = 502.9 kJ/kg</td>
</tr>
<tr>
<td>v_4 = v_{\text{TP}}(&quot;Air&quot;, T_4, p_4)</td>
<td>u_3 = 1803 kJ/kg</td>
</tr>
<tr>
<td>s_4 = s_{\text{TP}}(&quot;Air&quot;, T_4, p_4)</td>
<td>u_4 = 892.7 kJ/kg</td>
</tr>
<tr>
<td>u_4 = u_{\text{TP}}(&quot;Air&quot;, T_4)</td>
<td>v_1 = 0.861 m^3/\text{kg}</td>
</tr>
</tbody>
</table>

9-2
Thermal efficiency increases with increasing compression ratio. Since the heat addition is constant, the net work of the cycle increases, as expected. Also, the maximum cycle temperature increases, since the temperature at the end of compression, $T_s$, goes up with increasing $r$. The map increases as well for similar reasons.
PROBLEM 9.14

KNOWN: The bore, stroke, clearance volume, and speed of crankshaft rotation of a four-stroke, four-cylinder internal combustion engine are known. The processes within the cylinders are modeled by an Otto cycle with a known state at the beginning of compression and maximum cycle temperature.

FIND: Determine the net work per cycle and the power developed by the engine.

SCHEMATIC & GIVEN DATA:

\[ P \]

\[ T = 5200^\circ R \]

\[ T_i = 600^\circ F \]

\[ p_i = 14.6 \text{ lbf/in}^2 \]

\[ V_i = 3.75 \text{ in} \]

\[ V_s = 0.17 V_i \]

\[ V = 3.45 \text{ in} \]

\[ V_f = 0.17 V_i \]

\[ V = 2400 \text{ rev/min} \]

ASSUMPTIONS: Assumptions of Otto cycle are the same as in Example 9.1.

ANALYSIS: Using the given data,

\[ V_i - V_f = \frac{\pi}{4} (\text{bore})^2 \times (\text{stroke}) = \frac{\pi (3.75)(3.45)}{4} \text{ in}^3 = 144 \text{ in}^3 \]

\[ = 0.0208 \text{ ft}^3 \]

Thus, the mass of air is

\[ m = \frac{P_i V_i}{RT_i} = \frac{(144 \text{ in}^3)(0.0208 \text{ ft}^3)}{(1345 \text{ ft}^3/\text{lbm})(520^\circ R)} = 144 \text{ lbm} \]

Next, fix each of the principal states of the cycle. From Table A-12E, at \( T_i = 520^\circ R \), \( U_i = 88.82 \text{ Btu/lbm} \), \( V_i = 138.58 \). Further, the compression is \( V_i/V_n = 5.88 \). Thus, for the isentropic compression

\[ V_f = \frac{V_i}{V_n} = \left(\frac{1}{5.88}\right)138.58 = 23.67 \]

Thus, we get \( u_2 = 180.12 \text{ Btu/lbm} \) at \( T_2 = 5200^\circ R \), \( u_3 = 1098.0 \text{ Btu/lbm} \) and \( u_3 = 0.18 \). For the isentropic expansion,

\[ V_n = \frac{V_i}{V_n} = \frac{V_i}{V_f} = 1.075 \]

Using this, we get \( u_4 = 694.62 \text{ Btu/lbm} \).

The net work per cycle is

\[ W_{cycle} = Q_{23} - Q_{41} = m [(u_3 - u_2) - (u_4 - u_i)] \]

\[ = (0.0208 \text{ lbm})[(1098.0 - 180.12) - (694.62 - 88.82)] \text{ Btu/lbm} \]

\[ = 0.812 \text{ Btu} \]

For a four-stroke engine, the cycle is completed once for every two revolutions of the crankshaft. For four cylinders, the net power is

\[ W_{net} = \frac{(4)(3600 \text{ cycles/min})(0.812 \text{ Btu/cycle})}{1440 \text{ BHP}} = 91.5 \text{ HP} \]
PROBLEM 9.19

KNOWN: An air-standard Diesel cycle has a specified state at the beginning of compression and a known pressure and temperature at the end of heat addition.

ENDS: Determine (a) the compression ratio, (b) the cutoff ratio, (c) the thermal efficiency, and (d) the mean effective pressure.

SCHEMATIC & GIVEN DATA:

\[ P_1 = P_3 = 6.8 \text{ MPa} = 6500 \text{ kPa} \]

\[ T_3 = 2000K \]

\[ P_4 = 95 \text{ kPa} \]

\[ T_4 = 290K \]

ASSUMPTIONS: See Example 9.2.

ANALYSIS: Begin by fixing each principal state in the cycle (Table A-12).

State 1: \( T_1 = 290K, P_1 = 95 \text{ kPa} \) \( \Rightarrow u_1 = 206.91 \text{ kJ/kg} \), \( v_{p1} = 676.1, P_r = 1.2311 \)

State 2: For the isentropic compression,

\[ P_{r2} = P_1 \left( \frac{P_4}{P_3} \right) = (1.2311) \left( \frac{95}{6500} \right) = 0.023 \]

Thus, \( T_2 = 926K, v_{r2} = 31.618 \), \( h_2 = 962.19 \text{ kJ/kg} \)

State 3: \( T_3 = 2000K, P_3 = 6500 \text{ kPa} \) \( \Rightarrow h_3 = 2252.1 \text{ kJ/kg} \), \( v_{r3} = 2.776 \)

State 4: For the isentropic expansion

\[ \frac{v_4}{v_3} = \frac{v_r}{v_2}, \frac{T_4}{T_3} = \frac{x_4}{x_3}, \frac{T_4}{T_3} = \frac{6781.1}{31.618} = 2000 = 9.9 \]

\[ v_4 = \frac{v_3 v_r}{v_2}, v_4 = 27.48 \] \( \Rightarrow T_4 = 971K, w_4 = 734.36 \text{ kJ/kg} \)

(a) The compression ratio is

\[ r = \frac{v_2}{v_3} = \frac{v_r}{v_2} = 31.618 = 21.38 \]

(b) The cutoff ratio is

\[ f_c = \frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{2000}{926} = 2.16 \]

(c) The thermal efficiency is

\[ \eta = \frac{w_{out}}{Q_{in}} = \frac{(h_3 - h_2) - (w_3 - w_1)}{h_3 - h_2} = \frac{(2252.1 - 962.19) - (734.36 - 206.91)}{2252.1 - 962.19} = \frac{1189.91}{1289.91} = 0.91 (91.1\%) \]

9-31
PROBLEM 9.19 (Cont'd)

(a) The mean effective pressure is given as

\[ \text{mep} = \frac{\text{Wcycle}}{V_1 - V_2} = \frac{\text{Wcycle}(m)}{V_1(1 - \frac{V_2}{V_1})} \]

Evaluating \( V_1 \),

\[ V_1 = \frac{RT_1}{P_1} = \frac{(8.314 \text{ kJ/kg} \cdot \text{K})(290 \text{ K})}{(95 \text{ kPa})} \]

\[ = \frac{1 \text{ kPa}}{10^3 \text{ N/m}^2} \]

\[ = 0.8761 \text{ m}^2/\text{kg} \]

Thus

\[ \text{mep} = \frac{(762.46 \text{ kJ/kg})}{(0.8761 \text{ m}^2/\text{kg})(1 - \frac{1}{21.38})} \]

\[ = 913 \text{ kPa} \]
PROBLEM 9.30

**KNOWN**: Operating data are provided for an air-standard Diesel cycle.

**FINISH**: Determine (a) the mass of air, (b) the heat addition and heat rejection per cycle, (c) the net work and the thermal efficiency.

**SCHEMATIC & GIVEN DATA:**

```
```

**ASSUMPTIONS**:
See Example 9.2

**ANALYSIS**: The mass \( m \)

\[
\frac{m}{R_T} = \left( \frac{96.0 \text{m}^3}{m^2} \right) \left( \frac{0.016 \text{m}^3}{287 \text{kJ/m}^3} \right) (290 \text{K})
\]

\( m = 1.846 \times 10^{-3} \text{kg} \)

Next, for each of the principal states:

**State 1**: at \( T_1 = 290 \text{K} \), Table A-22 gives

\( u_1 = 206.91 \text{kJ/kg} \), \( v_1 = 6.961 \). **State 2**: for the isentropic compression

\( v_2 = \frac{v_1}{\frac{k}{k-1}} = \frac{6.961}{\frac{1.4}{1.4-1}} = 4.507 \text{ m}^3/\text{kg} \), \( T_2 = 818.6 \text{ K} \), \( h_2 = 842.4 \text{ kJ/kg} \). **State 3**: \( m \cdot h_3 = 1290 \text{ kJ} \).

\( h_3 = 1394.11 \text{ kJ/kg} \), \( v_3 = 11.555 \). **State 4**: For the isentropic expansion

\( v_4 = \frac{v_3}{\frac{k}{k-1}} = \frac{11.555}{\frac{1.4}{1.4-1}} = 7.839 \text{ m}^3/\text{kg} \), \( T_4 = 818.6 \text{ K} \), \( h_4 = 842.4 \text{ kJ/kg} \).

Thus, \( u_4 = 445.12 \text{ kJ/kg} \).

The heat addition is \( Q_{23} = m (h_3 - h_2) = (1.846 \times 10^{-3}) (1394.11 - 842.4) = 10.0 \text{ kJ} \)

The heat rejection is \( Q_{41} = m (u_4 - u_1) = (1.846 \times 10^{-3}) (445.12 - 206.91) = 4.08 \text{ kJ} \)

For any cycle, \( W_{cycle} = W_{boyle} \). Thus

\( W_{boyle} = Q_{23} - Q_{41} = 10.0 \text{ kJ} - 4.08 \text{ kJ} = 5.92 \text{ kJ} \)

The thermal efficiency is

\[ \eta = \frac{W_{boyle}}{Q_{23}} = 5.92 \times 10^{-2} (5.92 \%) \]