Liquid propane is burned with dry air. A volumetric analysis of the products of combustion yields the following volume percent composition on a dry basis: 8.6% CO₂, 0.6% CO, 7.2% O₂ and 83.6% N₂. Determine the percent of theoretical air used in this combustion process.

\[
a C_3H_8 + b O_2 + c N_2 \rightarrow 8.6 \text{ CO}_2 + 0.6 \text{ CO} + d \text{H}_2O + 7.2 \text{ O}_2 + 83.6 \text{ N}_2
\]

C balance: \[3a = 8.6 + 0.6 = 9.2 \Rightarrow a = 3.067\]

H₂ balance: \[4a = d \Rightarrow d = 12.267\]

N₂ balance: \[c = 83.6\]

O₂ balance: \[b = 8.6 + \frac{0.6}{2} + \frac{12.267}{2} + 7.2 = 22.234\]

Air-Fuel ratio = \[\frac{22.234 + 83.6}{3.067} = 34.51\]

Theoretical:
\[
C_3H_8 + 5 O_2 + 18.8 N_2 \rightarrow 3 \text{ CO}_2 + 4 \text{ H}_2O + 18.8 \text{ N}_2
\]

⇒ theo. A-F ratio = \[\frac{5 + 18.8}{1} = 23.8\]

\[\% \text{ theoretical air} = \frac{34.51}{23.8} \times 100 \% = 145 \%\]
15.31

Butane is burned with dry air at 40°C, 100 kPa with AF = 26 on a mass basis. For complete combustion find the equivalence ratio, % theoretical air and the dew point of the products. How much water (kg/kg fuel) is condensed out, if any, when the products are cooled down to ambient temperature?

Solution:

\[
\text{C}_4\text{H}_{10} + \nu \text{O}_2 (\text{O}_2 + 3.76 \text{N}_2) \rightarrow 4 \text{CO}_2 + 5 \text{H}_2\text{O} + 3.76 \nu \text{O}_2 \text{N}_2
\]

Stoichiometric \( \nu \text{O}_2 \text{S} = 4 + 5/2 = 6.5; \quad 3.76 \nu \text{O}_2 = 24.44 \)

\( (\text{A/F})_S = 6.5(31.999 + 3.76 \times 28.013)/58.124 = 15.3574 \)

Actual:

\( \nu \text{O}_2 \text{ac} = \frac{(\text{A/F})_\text{ac}}{(\text{A/F})_S} \nu \text{O}_2 \text{S} = \frac{26}{15.3574} \times 6.5 = 11 \)

% Theoretical air = \( \frac{26}{15.3574} \times 100 = 169.3\% \)

Equivalence ratio \( \Phi = 1/1.693 = 0.59 \)

Actual products: \( 4 \text{CO}_2 + 5 \text{H}_2\text{O} + 4.5 \text{O}_2 + 41.36 \text{N}_2 \)

The water partial pressure becomes

\[ P_v = y_v P_{\text{tot}} = \frac{5}{4 + 5 + 4.5 + 41.36} \times 100 = 9.114 \text{ kPa} \]

\[ T_{\text{dew}} = 43.85^\circ \text{C} \]

\[ P_{\text{g 40}} = 7.348 \text{ kPa} \quad \Rightarrow \quad y_v \text{ max} = \frac{7.384}{100} = \frac{\nu \text{H}_2\text{O}}{4 + \nu \text{H}_2\text{O} + 4.5 + 41.36} \]

Solve for \( \nu \text{H}_2\text{O} \text{ vap} \):

\[ \nu \text{H}_2\text{O} \text{ vap} = 3.975 \quad \text{still vapor,} \]

\[ \nu \text{H}_2\text{O LIQ} = 5 - 3.975 = 1.025 \quad \text{is liquid} \]

\[ \frac{m \text{H}_2\text{O LIQ}}{m_{\text{Fuel}}} = 1.025 \times 18.015 \times \frac{58.124}{58.124} = 0.318 \]
15.69

Natural gas, we assume methane, is burned with 200% theoretical air and the reactants are supplied as gases at the reference temperature and pressure. The products are flowing through a heat exchanger where they give off energy to some water flowing in at 20°C, 500 kPa and out at 700°C, 500 kPa. The products exit at 400 K to the chimney. How much energy per kmole fuel can the products deliver and how many kg water per kg fuel can they heat?

The reaction equation for stoichiometric mixture is:

\[
\text{CH}_4 + \nu_{O_2} \left( O_2 + 3.76 \text{ N}_2 \right) \rightarrow 2 \text{H}_2\text{O} + 1 \text{ CO}_2 + c \text{ N}_2
\]

O balance: \(2 \cdot \nu_{O_2} = 2 + 2\) \(\Rightarrow\) \(\nu_{O_2} = 2\)

200% theoretical air: \(\nu_{O_2} = 2 \times 2 = 4\) \(\Rightarrow\) so now more \(O_2\) and \(N_2\)

\[
\text{CH}_4 + 4 \left( O_2 + 3.76 \text{ N}_2 \right) \rightarrow 2 \text{H}_2\text{O} + 1 \text{ CO}_2 + 15.04 \text{ N}_2 + 2 \text{ O}_2
\]

The products are cooled to 400 K (so we do not consider condensation) and the energy equation is

\[
\text{Energy Eq.:} \quad H_R + Q = H_P = H_P^\circ + \Delta H_P = H_R^\circ + Q
\]

\[
Q = H_P^\circ - H_R^\circ + \Delta H_P = H_{RP}^\circ + \Delta H_P
\]

From Table 15.3: \(H_{RP}^\circ = 16.04 \times (-50\ 010) = -802\ 160 \text{ kJ/kmol}\)

\[
\Delta H_P = \Delta h_{CO_2}^* + 2 \Delta h_{H_2O}^* + 2 \Delta h_{O_2}^* + 15.04 \Delta h_{N_2}^*
\]

From Table A.9

\[
\Delta H_{P\ 400} = 4003 + 2 \times 3450 + 2 \times 3027 + 15.04 \times 2971 = 61\ 641 \text{ kJ/kmol}
\]

\[
Q = H_{RP}^\circ + \Delta H_P = -802\ 160 + 61\ 641 = -\textbf{740\ 519 kJ/kmol}
\]

\[
q_{\text{prod}} = -Q / M = 740\ 519 / 16.04 = 46\ 167 \text{ kJ/kg fuel}
\]

The water flow has a required heat transfer, using B.1.3 and B.1.4 as

\[
q_{\text{H}_2\text{O}} = h_{\text{out}} - h_{\text{in}} = 3925.97 - 83.81 = 3842.2 \text{ kJ/kg water}
\]

The mass of water becomes

\[
\frac{m_{\text{H}_2\text{O}}}{m_{\text{fuel}}} = \frac{q_{\text{prod}}}{q_{\text{H}_2\text{O}}} = \textbf{12.0 kg water / kg fuel}
\]
Gasoline, \( C_7H_{17} \), is burned in a steady state burner with stoichiometric air at \( P_o \), \( T_o \). The gasoline is flowing as a liquid at \( T_o \) to a carburetor where it is mixed with air to produce a fuel air gas mixture at \( T_o \). The carburetor takes some heat transfer from the hot products to do the heating. After the combustion the products go through a heat exchanger, which they leave at 600 K. The gasoline consumption is 10 kg per hour. How much power is given out in the heat exchanger and how much power does the carburetor need?

**Stoichiometric combustion:**

\[
C_7H_{17} + \nu_{O_2} \left( O_2 + 3.76 \, N_2 \right) \rightarrow 8.5 \, H_2O + 7 \, CO_2 + c \, N_2
\]

O balance: \( 2 \, \nu_{O_2} = 8.5 + 14 = 22.5 \quad \Rightarrow \quad \nu_{O_2} = 11.25 \)

N balance: \( c = 3.76 \, \nu_{O_2} = 3.76 \times 11.25 = 42.3 \)

\[ M_{\text{FUEL}} = 7 \, M_C + 17 \, M_H = 7 \times 12.011 + 8.5 \times 2.016 = 101.213 \]

**C.V. Total, heat exchanger and carburetor included, Q out.**

Energy Eq.: \( H_R = H_R^\circ = H_P^\circ + \Delta H_P + Q_{\text{out}} \)

From Table A.9
\[ \Delta H_P = 8.5 \times 10 \, 499 + 7 \times 12 \, 906 + 42.3 \times 8894 = 555 \, 800 \, \text{kJ/kmol} \]

From energy equation and Table 15.3
\[
Q_{\text{out}} = H_R^\circ - H_P^\circ - \Delta H_P = -H_{RP}^\circ - \Delta H_P = 101.213 \left( 44 \, 506 \right) - 555 \, 800 = 3 \, 948 \, 786 \, \text{kJ/kmol}
\]

Now the power output is
\[
\dot{Q} = \dot{m} \, Q_{\text{out}} = \frac{10}{3600} \times \frac{3 \, 948 \, 786}{101.213} = \textbf{108.4 kW}
\]

The carburetor air comes in and leaves at the same \( T \) so no change in energy, all we need is to evaporate the fuel, \( h_{fg} \) so

\[
\dot{Q} = \dot{m} \, h_{fg} = \frac{10}{3600} \left( 44 \, 886 - 44 \, 506 \right) = \frac{1}{360} \times 380 = \textbf{1.06 kW}
\]

Here we used Table 15.3 for fuel liquid and fuel vapor to get \( h_{fg} \) and any phase of the water as long as it is the same for the two.
A gas turbine burns methane with 200% theoretical air. The air and fuel come in through two separate compressors bringing them from 100 kPa, 298 K to 1400 kPa and after mixing enters the combustion chamber at 600 K. Find the adiabatic flame temperature using constant specific heat for the $\Delta H_p$ terms.

The reaction equation for a stoichiometric mixture is:

$$\text{CH}_4 + \nu_{O_2} \left( O_2 + 3.76 \text{ N}_2 \right) \rightarrow 2 \text{ H}_2\text{O} + 1 \text{ CO}_2 + c \text{ N}_2$$

O balance: $2 \nu_{O_2} = 2 + 2 \Rightarrow \nu_{O_2} = 2$

200% theoretical air: $\nu_{O_2} = 2 \times 2 = 4$ so now more O$_2$ and N$_2$

$$\text{CH}_4 + 4 \left( O_2 + 3.76 \text{ N}_2 \right) \rightarrow 2 \text{ H}_2\text{O} + 1 \text{ CO}_2 + 15.04 \text{ N}_2 + 2 \text{ O}_2$$

The energy equation around the combustion chamber becomes

\[
\text{Energy Eq.: } H_p - H_R = 0 \Rightarrow \Delta H_p = H_R^\circ + \Delta H_R - H_p = -H_{RP} + \Delta H_R
\]

\[
\Delta H_R = \Delta H_{\text{Fuel}} + \Delta H_{\text{air}} = M \ C_P \ \Delta T + 4(\Delta \tilde{h}_{O_2} + 3.76 \ \Delta \tilde{h}_{\text{N}_2})
\]

\[
= 16.043 \times 2.254 \ (600-298) + 4(9245 + 3.76 \times 8894) = 181 \ 666 \ \text{kJ/kmol}
\]

\[-H_{RP} = 16.043 \times 50 \ 010 = 802 \ 310 \ \text{kJ/kmol}
\]

\[
\Delta H_p = \Delta \tilde{h}_{\text{CO}_2} + 2 \ \Delta \tilde{h}_{\text{H}_2\text{O}} + 15.04 \ \Delta \tilde{h}_{\text{N}_2} + 4 \ \Delta \tilde{h}_{O_2} \approx \Delta T \sum \nu_i \tilde{C}_p_i
\]

\[
\sum \nu_i \tilde{C}_p_i = 0.842 \times 44.01 + 2 \times 1.872 \times 18.015 + 15.04 \times 1.042 \times 28.013
\]

\[
+ 2 \times 0.922 \times 31.999 = 602.52 \ \text{kJ/kmol-K}
\]

\[
\Delta T = \Delta H_p / \sum \nu_i \tilde{C}_p_i = 983 \ 976 / 602.52 = 1633.1 \ \text{K}
\]

\[
T = 298 + 1633 = 1931 \ \text{K}
\]
Extend the solution to the previous problem by using Table A.9 for the $\Delta H_p$ terms.

The reaction equation for stoichiometric mixture is:

$$\text{CH}_4 + \nu \text{O}_2 \left( \text{O}_2 + 3.76 \text{N}_2 \right) \rightarrow 2 \text{H}_2\text{O} + 1 \text{CO}_2 + c \text{N}_2$$

O balance: $2 \nu \text{O}_2 = 2 + 2$  \Rightarrow  $\nu \text{O}_2 = 2$

200% theoretical air: $\nu \text{O}_2 = 2 \times 2 = 4$  \Rightarrow  now more O$_2$ and N$_2$

$$\text{CH}_4 + 4 \left( \text{O}_2 + 3.76 \text{N}_2 \right) \rightarrow 2 \text{H}_2\text{O} + 1 \text{CO}_2 + 15.04 \text{N}_2 + 2 \text{O}_2$$

The energy equation around the combustion chamber becomes

Energy Eq. $\left( H_p - H_R = 0 \right)$  \Rightarrow  $\Delta H_p = H_R^0 + \Delta H_R - H_P^0 = -H_{RP} + \Delta H_R$

$$\Delta H_R = \Delta H_{\text{Fuel}} + \Delta H_{\text{air}} = M \ C_P \ \Delta T + 4(\Delta h_{\text{O}_2} + 3.76 \Delta h_{\text{N}_2})$$

$$= 16.043 \times 2.254 \ (600–298) + 4(9245 + 3.76 \times 8894) = 181 666 \text{ kJ/kmol}$$

$-H_{RP} = 16.043 \times 50 010 = 802 310 \text{ kJ/kmol}$

$$\Delta H_p = \Delta h_{\text{CO}_2} + 2 \Delta h_{\text{H}_2\text{O}} + 15.04 \Delta h_{\text{N}_2} + 2 \Delta h_{\text{O}_2}$$

$$= 802 310 + 181 666 = 983 976 \text{ kJ/kmol} \ \ (\text{from energy Eq.})$$

Trial and error with $\Delta h$ from Table A.9

At 1800 K

$$\Delta H_p = 79 432 + 2 \times 62 693 + 15.04 \times 48 979 + 2 \times 51 674 = 1 044 810 \text{ kJ/kmol}$$

At 1700 K

$$\Delta H_p = 73 480 + 2 \times 57 757 + 15.04 \times 45 430 + 2 \times 47 959 = 968 179 \text{ kJ/kmol}$$

Linear interpolation: \quad $T = 1700 + 100 \frac{983 976 - 968 179}{1 044 810 - 968 179} = 1721 \text{ K}$
15.83

Acetylene gas at 25°C, 100 kPa is fed to the head of a cutting torch. Calculate the adiabatic flame temperature if the acetylene is burned with

a. 100% theoretical air at 25°C.

b. 100% theoretical oxygen at 25°C.

a) \[ \text{C}_2\text{H}_2 + 2.5 \text{ O}_2 + 2.5 \times 3.76 \text{ N}_2 \rightarrow 2 \text{ CO}_2 + 1 \text{ H}_2\text{O} + 9.4 \text{ N}_2 \]

\[ H_R = h^0_{\text{C}_2\text{H}_2} = +226 \, 731 \, \text{kJ/kmol} \quad \text{from table A.10} \]

\[ H_p = 2(-393 \, 522 + \Delta h^*_{\text{CO}_2}) + 1(-241 \, 826 + \Delta h^*_{\text{H}_2\text{O}}) + 9.4 \Delta h^*_{\text{N}_2} \]

\[ Q_{CV} = H_p - H_R = 0 \quad \Rightarrow \quad 2 \Delta h^*_{\text{CO}_2} + 1 \Delta h^*_{\text{H}_2\text{O}} + 9.4 \Delta h^*_{\text{N}_2} = 1 \, 255 \, 601 \, \text{kJ} \]

Trial and Error A.9: \[ \text{LHS}_{2800} = 1 \, 198 \, 369, \quad \text{LHS}_{3000} = 1 \, 303 \, 775 \]

Linear interpolation: \[ T_{\text{PROD}} = 2909 \, \text{K} \]

b) \[ \text{C}_2\text{H}_2 + 2.5 \text{ O}_2 \rightarrow 2 \text{ CO}_2 + \text{ H}_2\text{O} \]

\[ H_R = +226 \, 731 \, \text{kJ} ; \quad H_p = 2(-393 \, 522 + \Delta h^*_{\text{CO}_2}) + 1(-241 \, 826 + \Delta h^*_{\text{H}_2\text{O}}) \]

\[ \Rightarrow \quad 2 \Delta h^*_{\text{CO}_2} + 1 \Delta h^*_{\text{H}_2\text{O}} = 1 \, 255 \, 601 \, \text{kJ/kmol fuel} \]

At 6000 K (limit of A.9) \[ 2 \times 343 \, 782 + 302 \, 295 = 989 \, 859 \]

At 5600 K \[ 2 \times 317 \, 870 + 278 \, 161 = 913 \, 901 \]

Slope \[ 75 \, 958/400 \, \text{K change} \]

Extrapolate to cover the difference above 989 859 kJ/kmol fuel

\[ T_{\text{PROD}} \approx 6000 + 400(265 \, 742/75 \, 958) \approx 7400 \, \text{K} \]
Consider the combustion of methanol, CH$_3$OH, with 25% excess air. The combustion products are passed through a heat exchanger and exit at 200 kPa, 400 K. Calculate the absolute entropy of the products exiting the heat exchanger assuming all the water is vapor.

$$\text{CH}_3\text{OH} + 1.25 \times 1.5 (\text{O}_2 + 3.76 \text{N}_2) \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} + 0.375 \text{O}_2 + 7.05 \text{N}_2$$

We need to find the mole fractions to do the partial pressures,

$$n = 1 + 2 + 0.375 + 7.05 = 10.425 \quad \Rightarrow \quad y_i = \frac{n_i}{n}$$

<table>
<thead>
<tr>
<th>Gas mixture:</th>
<th>$n_i$</th>
<th>$y_i$</th>
<th>$\tilde{s}_i^0$</th>
<th>$\frac{-\tilde{R} \ln \frac{y_i P}{P_0}}{\tilde{S}_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>1.0</td>
<td>0.0959</td>
<td>225.314</td>
<td>13.730</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>2</td>
<td>0.1918</td>
<td>198.787</td>
<td>7.967</td>
</tr>
<tr>
<td>O$_2$</td>
<td>0.375</td>
<td>0.0360</td>
<td>213.873</td>
<td>20.876</td>
</tr>
<tr>
<td>N$_2$</td>
<td>7.05</td>
<td>0.6763</td>
<td>200.181</td>
<td>-2.511</td>
</tr>
</tbody>
</table>

$$S_{\text{GAS MIX}} = \sum n_i\tilde{S}_i = 2134.5 \text{ kJ/K kmol fuel}$$
15.94

Propene, $\text{C}_3\text{H}_6$, is burned with air in a steady flow burner with reactants at $P_0$, $T_0$. The mixture is lean so the adiabatic flame temperature is 1800 K. Find the entropy generation per kmol fuel neglecting all the partial pressure corrections.

The reaction equation for a mixture with excess air is:

$$\text{C}_3\text{H}_6 + ν_{\text{O}_2} \left(\text{O}_2 + 3.76 \text{ N}_2\right) \rightarrow 3\text{ H}_2\text{O} + 3\text{ CO}_2 + 3.76ν_{\text{O}_2} \text{ N}_2 + (ν_{\text{O}_2} - 4.5)\text{O}_2$$

Energy Eq.: 

$$H_R = H^\circ_R + \Delta H_R = H^\circ_R = H_p = H^\circ_p + \Delta H_p$$

The entropy equation: 

$$S_R + S_{\text{gen}} = S_p \Rightarrow S_{\text{gen}} = S_p - S_R = S_p - S^\circ_R$$

From table A.9 at reference $T$

$$\Delta H_R = \Delta h_{\text{Fu}} + ν_{\text{O}_2}\left(\Delta h_{\text{O}_2} + 3.76 \Delta h_{\text{N}_2}\right) = 0$$

From table A.9 at 1800 K:

$$\Delta H_p = 3 \Delta h_{\text{H}_2\text{O}} + 3 \Delta h_{\text{CO}_2} + 3.76 ν_{\text{O}_2} \Delta h_{\text{N}_2} + (ν_{\text{O}_2} - 4.5) \Delta h_{\text{O}_2}$$

$$= 3 \times 62 693 + 3 \times 79432 + 3.76 ν_{\text{O}_2} \times 48 979 + (ν_{\text{O}_2} - 4.5) 51 674$$

$$= 193 842 + 235 835 ν_{\text{O}_2}$$

From table 15.3: 

$$H^\circ_p - H^\circ_R = H^\circ_{\text{RP}} = 42.081(-45 780) = -1 926 468 \text{ kJ/kmol}$$

Now substitute all terms into the energy equation

$$−1 926 468 + 193 842 + 235 835 ν_{\text{O}_2} = 0$$

Solve for $ν_{\text{O}_2}$:

$$ν_{\text{O}_2} = \frac{1 926 468 - 193 842}{235 835} = 7.3468, \quad ν_{\text{N}_2} = 27.624$$

Table A.9-10 contains the entropies at 100 kPa so we get:

$$S_p = 3 \times 259.452 + 3 \times 302.969 + (7.3468 - 4.5) 264.797 + 27.624 \times 248.304$$

$$= 9300.24 \text{ kJ/kmol-K}$$

$$S_R = 267.066 + 7.3468 \times 205.148 + 27.624 \times 191.609 = 7067.25 \text{ kJ/kmol K}$$

$$S_{\text{gen}} = 9300.24 - 7067.25 = 2233 \text{ kJ/kmol-K}$$