A mixture of 40% by volume methane, CH₄, and 60% by volume propane, C₃H₈, is burned completely with theoretical air. The amount of water formed during combustion process that will be condensed is to be determined.

**Assumptions** 1 Combustion is complete. 2 The combustion products contain CO₂, H₂O, and N₂ only.

**Properties** The molar masses of C, H₂, O₂ and air are 12 kg/kmol, 2 kg/kmol, 32 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

**Analysis** The combustion equation in this case can be written as

\[ 0.4 \text{CH}_4 + 0.6 \text{C}_3\text{H}_8 + a_{th} \left[ \text{O}_2 + 3.76 \text{N}_2 \right] \rightarrow B \text{CO}_2 + D \text{H}_2\text{O} + F \text{N}_2 \]

where \(a_{th}\) is the stoichiometric coefficient for air. The coefficient \(a_{th}\) and other coefficients are to be determined from the mass balances:

Carbon balance: \( B = 0.4 + 3 \times 0.6 = 2.2 \)

Hydrogen balance: \( 2D = 4 \times 0.4 + 8 \times 0.6 = 2D \rightarrow D = 3.2 \)

Oxygen balance: \( 2a_{th} = 2B + D \rightarrow 2a_{th} = 2(2.2) + 3.2 \rightarrow a_{th} = 3.8 \)

Nitrogen balance: \( 3.76a_{th} = F \rightarrow 3.76(3.8) = F \rightarrow F = 14.29 \)

Then, we write the balanced reaction equation as

\[ 0.4 \text{CH}_4 + 0.6 \text{C}_3\text{H}_8 + 3.8 \left[ \text{O}_2 + 3.76 \text{N}_2 \right] \rightarrow 2.2 \text{CO}_2 + 3.2 \text{H}_2\text{O} + 14.29 \text{N}_2 \]

The vapor mole fraction in the products is

\[ y_v = \frac{3.2}{2.2 + 3.2 + 14.29} = 0.1625 \]

The partial pressure of water in the products is

\[ P_{v, prod} = y_v P_{prod} = (0.1625)(100 \text{kPa}) = 16.25 \text{kPa} \]

The dew point temperature of the products is

\[ T_{dp} = T_{sat@16.25 \text{kPa}} = 55.64^\circ \text{C} \]

The partial pressure of the water vapor remaining in the products at the product temperature is

\[ P_v = P_{sat@39^\circ \text{C}} = 7.0 \text{kPa} \]

The kmol of water vapor in the products at the product temperature is

\[ P_v = \frac{N_v}{N_{total, product}} P_{prod} \]

\[ 7.0 \text{kPa} = \frac{N_v}{2.2 + N_v + 14.29} \]

\[ N_v = 1.241 \text{kmol} \]

The kmol of water condensed is

\[ N_w = 3.2 - 1.241 = 1.96 \text{kmol water/kmol fuel} \]
15-103 Liquid propane, $\text{C}_3\text{H}_8$ (liq) is burned with 150 percent excess air. The balanced combustion equation is to be written and the mass flow rate of air, the average molar mass of the product gases, the average specific heat of the product gases at constant pressure are to be determined.

**Assumptions** 1 Combustion is complete. 2 The combustion products contain $\text{CO}_2$, $\text{H}_2\text{O}$, $\text{O}_2$, and $\text{N}_2$ only.

**Properties** The molar masses of $\text{C}$, $\text{H}_2$, $\text{O}_2$, and air are 12, 2, 32, 28, and 29 kg/kmol, respectively (Table A-1).

**Analysis** The reaction equation for 150% excess air is

\[
\text{C}_3\text{H}_8\text{(liq.)} + 2.5a_{\text{th}}[\text{O}_2 + 3.76\text{N}_2] \rightarrow B\text{ CO}_2 + D\text{ H}_2\text{O} + E\text{ O}_2 + F\text{ N}_2
\]

where $a_{\text{th}}$ is the stoichiometric coefficient for air. We have automatically accounted for the 150% excess air by using the factor $2.5a_{\text{th}}$ instead of $a_{\text{th}}$ for air. The coefficient $a_{\text{th}}$ and other coefficients are to be determined from the mass balances

- **Carbon balance:** $B = 3$
- **Hydrogen balance:** $2D = 8 \rightarrow D = 4$
- **Oxygen balance:** $2 \times 2.5a_{\text{th}} = 2B + D + 2E$

\[
a_{\text{th}} = E
\]

Nitrogen balance: $2.5a_{\text{th}} \times 3.76 = F$

Solving the above equations, we find the coefficients ($E = 7.5$, $F = 47$, and $a_{\text{th}} = 5$) and write the balanced reaction equation as

\[
\text{C}_3\text{H}_8 + 12.5[\text{O}_2 + 3.76\text{N}_2] \rightarrow 3\text{ CO}_2 + 4\text{ H}_2\text{O} + 7.5\text{ O}_2 + 47\text{ N}_2
\]

The fuel flow rate is

\[
\dot{m}_{\text{fuel}} = \frac{\dot{m}_{\text{fuel}}}{M_{\text{fuel}}} = \frac{0.4 \text{ kg/min}}{44 \text{ kg/kmol}} = 0.009071 \text{ kmol/min}
\]

The air-fuel ratio is determined by taking the ratio of the mass of the air to the mass of the fuel,

\[
\text{AF} = \frac{\dot{m}_{\text{air}}}{\dot{m}_{\text{fuel}}} = \frac{(12.5 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{(1 \text{ kmol})(44 \text{ kg/kmol})} = 39.08 \text{ kg air/kg fuel}
\]

Then, the mass flow rate of air becomes

\[
\dot{m}_{\text{air}} = \text{AF} \dot{m}_{\text{fuel}} = (39.08)(0.4 \text{ kg/min}) = 15.63 \text{ kg/min}
\]

The molar mass of the product gases is determined from

\[
M_{\text{prod}} = \frac{N_{\text{CO}_2}M_{\text{CO}_2} + N_{\text{H}_2\text{O}}M_{\text{H}_2\text{O}} + N_{\text{O}_2}M_{\text{O}_2} + N_{\text{N}_2}M_{\text{N}_2}}{N_{\text{CO}_2} + N_{\text{H}_2\text{O}} + N_{\text{O}_2} + N_{\text{N}_2}}
\]

\[
= \frac{3(44) + 4(18) + 7.5(32) + 47(28)}{3 + 4 + 7.5 + 47} = 28.63 \text{ kg/kmol}
\]

The steady-flow energy balance is expressed as

\[
\dot{N}_R H_R = \dot{Q}_{\text{exh}} + \dot{N}_{\text{fuel}} H_P
\]

where

\[
H_R = h_{\text{fuel}}^{25\circ\text{C}} + 12.5h_{\text{O}_2}^{25\circ\text{C}} + 47h_{\text{N}_2}^{25\circ\text{C}}
\]

\[
= (-103,847 \text{ kJ/kmol} - 40,525 \text{ kJ/kmol}) + 12.5(0) + 47(0) = -144,372 \text{ kJ/kmol}
\]
\[ H_p = 3\tilde{h}_{\text{CO}_2}T_p + 4\tilde{h}_{\text{H}_2\text{O}}T_p + 7.5\tilde{h}_{\text{O}_2}T_p + 47\tilde{h}_{\text{N}_2}T_p \]

Substituting into the energy balance equation,

\[ \dot{N}_{\text{fuel}}H_R = \dot{Q}_{\text{out}} + \dot{N}_{\text{fuel}}H_p \]

\[ (0.009071 \text{ kmol/min})(-144,372 \text{ kJ/kmol}) = (53 \times 60)\text{kJ/min} + (0.009071 \text{ kmol/min})H_p \]

\[ H_p = -150,215 \text{ kJ/kmol} \]

Substituting this value into the \( H_p \) relation above and by a trial-error approach or using EES, we obtain the temperature of the products of combustion

\[ T_p = 1282 \text{ K} \]

The average constant pressure specific heat of the combustion gases can be determined from

\[ C_{p,\text{prod}} = \frac{N_{\text{CO}_2}C_{\text{CO}_2}@1282\text{K} + N_{\text{H}_2\text{O}}C_{\text{H}_2\text{O}@1282\text{K}} + N_{\text{O}_2}C_{\text{O}_2}@1282\text{K} + N_{\text{N}_2}C_{\text{N}_2}@1282\text{K}}{N_{\text{CO}_2} + N_{\text{H}_2\text{O}} + N_{\text{O}_2} + N_{\text{N}_2}} \]

\[ = \frac{3(56.94) + 4(44.62) + 7.5(35.9) + 47(34.02)}{3 + 4 + 7.5 + 47} = 36.06 \text{ kJ/kmol} \cdot \text{K} \]

where the specific heat values of the gases are determined from EES.
A gaseous fuel mixture of 30% propane, \(C_3H_8\), and 70% butane, \(C_4H_{10}\), on a volume basis is burned with an air-fuel ratio of 20. The moles of nitrogen in the air supplied to the combustion process, the moles of water formed in the combustion process, and the moles of oxygen in the product gases are to be determined.

**Assumptions**
1. Combustion is complete.
2. The combustion products contain \(CO_2\), \(H_2O\), and \(N_2\) only.

**Properties**
The molar masses of \(C\), \(H_2\), \(O_2\) and air are 12 kg/kmol, 2 kg/kmol, 32 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

**Analysis**
The theoretical combustion equation in this case can be written as

\[
0.3\ C_3\ H_8 + 0.7\ C_4\ H_{10} + a_{th}[O_2 + 3.76N_2] \rightarrow B\ CO_2 + D\ H_2O + F\ N_2
\]

where \(a_{th}\) is the stoichiometric coefficient for air. The coefficient \(a_{th}\) and other coefficients are to be determined from the mass balances

- Carbon balance: \(B = 3\times 0.3 + 4\times 0.7 = 3.7\)
- Hydrogen balance: \(2D = 8\times 0.3 + 10\times 0.7 = 2D \rightarrow D = 4.7\)
- Oxygen balance: \(2a_{th} = 2B + D \rightarrow 2a_{th} = 2\times 3.7 + 4.7 \rightarrow a_{th} = 6.05\)
- Nitrogen balance: \(3.76a_{th} = F \rightarrow 3.76\times 6.05 = F \rightarrow F = 22.75\)

Then, we write the balanced theoretical reaction equation as

\[
0.3\ C_3\ H_8 + 0.7\ C_4\ H_{10} + 6.05[O_2 + 3.76N_2] \rightarrow 3.7\ CO_2 + 4.7\ H_2O + 22.75\ N_2
\]

The air-fuel ratio for the theoretical reaction is determined from

\[
AF_{th} = \frac{m_{air}}{m_{fuel}} = \frac{(6.05\times 4.75\ kmol)(29\ kg/kmol)}{(0.3\times 44 + 0.7\times 58)\ kg} = 15.47\ kg\ air/kg\ fuel
\]

The percent theoretical air is

\[
Percent TH_{air} = \frac{AF_{actual}}{AF_{th}} = \frac{20}{15.47}\times 100 = 129.3\%
\]

The moles of nitrogen supplied is

\[
N_{N_2} = \frac{Percent TH_{air} \times a_{th} \times 3.76}{100} = \frac{129.3}{100} \times (6.05)(3.76) = 29.41\ kmol\ per\ kmol\ fuel
\]

The moles of water formed in the combustion process is

\[
N_{H_2O} = D = 4.7\ kmol\ per\ kmol\ fuel
\]

The moles of oxygen in the product gases is

\[
N_{O_2} = \left(\frac{Percent TH_{air}}{100} - 1\right) a_{th} = \left(\frac{129.3}{100} - 1\right)(6.05) = 1.77\ kmol\ per\ kmol\ fuel
\]
15-105 A liquid gas fuel mixture consisting of 90% octane, C\textsubscript{8}H\textsubscript{18}, and 10% alcohol, C\textsubscript{2}H\textsubscript{5}OH, by moles is burned with 200% theoretical dry air. The balanced reaction equation for complete combustion of this fuel mixture is to be written, and the theoretical air-fuel ratio and the product-fuel ratio for this reaction, and the lower heating value of the fuel mixture with 200% theoretical air are to be determined.

**Assumptions**
1. Combustion is complete.
2. The combustion products contain CO\textsubscript{2}, H\textsubscript{2}O, O\textsubscript{2}, and N\textsubscript{2} only.

**Properties**
The molar masses of C, H\textsubscript{2}, O\textsubscript{2}, and air are 12, 2, 32, 28, and 29 kg/kmol, respectively (Table A-1).

**Analysis**
The reaction equation for 100% excess air is

$$0.9 \text{C}_8\text{H}_{18} (\text{liq}) + 0.1 \text{C}_2\text{H}_5\text{OH} + 2a_{th}[\text{O}_2 + 3.76\text{N}_2] \rightarrow B \text{ CO}_2 + D \text{ H}_2\text{O} + E \text{ O}_2 + F \text{ N}_2$$

where $a_{th}$ is the stoichiometric coefficient for air. We have automatically accounted for the 100% excess air by using the factor $2a_{th}$ instead of $a_{th}$ for air. The coefficient $a_{th}$ and other coefficients are to be determined from the mass balances:

- **Carbon balance:**
  $$8 \times 0.9 + 2 \times 0.1 = B \rightarrow B = 7.4$$

- **Hydrogen balance:**
  $$18 \times 0.9 + 6 \times 0.1 = 2D \rightarrow D = 8.4$$

- **Oxygen balance:**
  $$0.1 \times 1 + 2 \times 2a_{th} = 2B + D + 2E$$
  $$a_{th} = E$$

- **Nitrogen balance:**
  $$2a_{th} \times 3.76 = F$$

Solving the above equations, we find the coefficients ($E = 11.55$, $F = 86.86$, and $a_{th} = 11.55$) and write the balanced reaction equation as

$$0.9 \text{C}_8\text{H}_{18} (\text{liq}) + 0.1 \text{C}_2\text{H}_5\text{OH} + 23.1[\text{O}_2 + 3.76\text{N}_2] \rightarrow 7.4 \text{ CO}_2 + 8.4 \text{ H}_2\text{O} + 11.55 \text{ O}_2 + 86.86 \text{ N}_2$$

The theoretical air-fuel ratio is determined by taking the ratio of the mass of the air to the mass of the fuel for the theoretical reaction,

$$AF_{th} = \frac{m_{air}}{m_{fuel}} = \frac{a_{th} \times 4.76 \times M_{air}}{0.9 \times M_{C8H18} + 0.1 \times M_{C2H5OH}}$$

$$= \frac{(11.55 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{(0.9 \times 114 + 0.1 \times 46) \text{ kg}} = 14.83 \text{ kg air/kg fuel}$$

The actual air-fuel ratio is

$$AF_{actual} = 2AF_{th} = 2(14.83) = 29.65 \text{ kg air/kg fuel}$$

Then, the mass flow rate of air becomes

$$\dot{m}_{air} = AF_{actual}\dot{m}_{fuel} = (29.65)(5 \text{ kg/s}) = 148.3 \text{ kg/s}$$

The molar mass of the product gases is determined from

$$M_{prod} = \frac{N_{\text{CO}_2}M_{\text{CO}_2} + N_{\text{H}_2\text{O}}M_{\text{H}_2\text{O}} + N_{\text{O}_2}M_{\text{O}_2} + N_{\text{N}_2}M_{\text{N}_2}}{N_{\text{CO}_2} + N_{\text{H}_2\text{O}} + N_{\text{O}_2} + N_{\text{N}_2}}$$

$$= \frac{7.4(44) + 8.4(18) + 11.55(32) + 86.86(28)}{7.4 + 8.4 + 11.55 + 86.86}$$

$$= 28.72 \text{ kg/kmol}$$
The mass of product gases per unit mass of fuel is

$$m_{\text{prod}} = \frac{(N_{\text{CO}_2} + N_{\text{H}_2\text{O}} + N_{\text{O}_2} + N_{\text{N}_2})M_{\text{prod}}}{0.9 \times M_{\text{C}_8\text{H}_{18}} + 0.1 \times M_{\text{C}_2\text{H}_5\text{OH}}}$$

$$= \frac{(7.4 + 8.4 + 11.55 + 86.86)(28.72 \text{ kg/kgmol})}{(0.9 \times 114 + 0.1 \times 46)\text{kg}} = 30.54 \text{ kg product/kg fuel}$$

The steady-flow energy balance can be expressed as

$$H_R = \bar{q}_{\text{LHV}} + H_P$$

where

$$H_R = 0.9(\bar{h}_{\text{C}_8\text{H}_{18}\text{g}25^\circ\text{C}} - \bar{h}_{f,l,\text{C}_8\text{H}_{18}}) + 0.1(\bar{h}_{\text{C}_2\text{H}_5\text{OH}\text{g}25^\circ\text{C}} - \bar{h}_{f,l,\text{C}_2\text{H}_5\text{OH}}) + 23.1\bar{h}_{\text{O}_2\text{g}25^\circ\text{C}} + 86.86\bar{h}_{\text{N}_2\text{g}25^\circ\text{C}}$$

$$= 0.9(-208,459 - 41,465) + 0.1(-235,310 - 42,340) + 23.1(0) + 86.86(0)$$

$$= -252,697 \text{ kJ/kmol}$$

$$H_P = 7.4\bar{h}_{\text{CO}_2\text{g}25^\circ\text{C}} + 8.4\bar{h}_{\text{H}_2\text{O}\text{g}25^\circ\text{C}} + 11.55\bar{h}_{\text{N}_2\text{g}25^\circ\text{C}} + 86.86\bar{h}_{\text{N}_2\text{g}25^\circ\text{C}}$$

$$= 7.4(-393,520) + 8.4(-241,820) + 11.55(0) + 86.86(0)$$

$$= -4.943 \times 10^6 \text{ kJ/kmol}$$

Substituting, we obtain

$$\bar{q}_{\text{LHV}} = 4.691 \times 10^6 \text{ kJ/kmol}$$

The lower heating value on a mass basis is determined to be

$$q_{\text{LHV}} = \frac{\bar{q}_{\text{LHV}}}{0.9 \times M_{\text{C}_8\text{H}_{18}} + 0.1 \times M_{\text{C}_2\text{H}_5\text{OH}}}$$

$$= \frac{4.691 \times 10^6 \text{ kJ/kmol}}{(0.9 \times 114 + 0.1 \times 46)\text{kg/kmol}} = 43,672 \text{ kJ/kg of fuel}$$
It is to be shown that the work output of the Carnot engine will be maximum when \( T_p = \sqrt{T_0 T_{af}} \). It is also to be shown that the maximum work output of the Carnot engine in this case becomes
\[
w = C T_{af} \left( 1 - \frac{\sqrt{T_0}}{\sqrt{T_{af}}} \right)^2.
\]

**Analysis** The combustion gases will leave the combustion chamber and enter the heat exchanger at the adiabatic flame temperature \( T_{af} \) since the chamber is adiabatic and the fuel is burned completely. The combustion gases experience no change in their chemical composition as they flow through the heat exchanger. Therefore, we can treat the combustion gases as a gas stream with a constant specific heat \( c_p \). Noting that the heat exchanger involves no work interactions, the energy balance equation for this single-stream steady-flow device can be written as
\[
\dot{Q} = \dot{m}(h_f - h_i) = \dot{m}C(T_p - T_{af})
\]
where \( \dot{Q} \) is the negative of the heat supplied to the heat engine. That is,
\[
\dot{Q}_{HT} = -\dot{Q} = \dot{m}C(T_{af} - T_p)
\]
Then the work output of the Carnot heat engine can be expressed as
\[
\dot{W} = \dot{Q}_{HT} \left( 1 - \frac{T_0}{T_p} \right) = \dot{m}C(T_{af} - T_p) \left( 1 - \frac{T_0}{T_p} \right) \tag{1}
\]
Taking the partial derivative of \( \dot{W} \) with respect to \( T_p \) while holding \( T_{af} \) and \( T_0 \) constant gives
\[
\frac{\partial \dot{W}}{\partial T_p} = 0 \quad \longrightarrow \quad -\dot{m}C \left( 1 - \frac{T_0}{T_p} \right) + \dot{m}C(T_p - T_{af}) \frac{T_0 T_p}{T_p^2} = 0
\]
Solving for \( T_p \) we obtain
\[
T_p = \sqrt{T_0 T_{af}}
\]
which the temperature at which the work output of the Carnot engine will be a maximum. The maximum work output is determined by substituting the relation above into Eq. (1),
\[
\dot{W} = \dot{m}C(T_{af} - T_p) \left( 1 - \frac{T_0}{T_p} \right) = \dot{m}C(T_{af} - \sqrt{T_0 T_{af}}) \left( 1 - \frac{T_0}{\sqrt{T_0 T_{af}}} \right)
\]
It simplifies to
\[
\dot{W} = \dot{m}C T_{af} \left( 1 - \frac{\sqrt{T_0}}{\sqrt{T_{af}}} \right)^2
\]
or
\[
w = C T_{af} \left( 1 - \frac{\sqrt{T_0}}{\sqrt{T_{af}}} \right)^2
\]
which is the desired relation.
It is to be shown that the work output of the reversible heat engine operating at the specified conditions is \( W_{\text{rev}} = \dot{m}CT_0\left(\frac{T_{\text{af}}}{T_0} - 1 - \ln\frac{T_{\text{af}}}{T_0}\right) \). It is also to be shown that the effective flame temperature \( T_e \) of the furnace considered is
\[
T_e = \frac{T_{\text{af}} - T_0}{\ln\left(\frac{T_{\text{af}}}{T_0}\right)}.
\]

**Analysis** The combustion gases will leave the combustion chamber and enter the heat exchanger at the adiabatic flame temperature \( T_{\text{af}} \) since the chamber is adiabatic and the fuel is burned completely. The combustion gases experience no change in their chemical composition as they flow through the heat exchanger. Therefore, we can treat the combustion gases as a gas stream with a constant specific heat \( c_p \).

The work output of the reversible heat engine is equal to the reversible work \( W_{\text{rev}} \) of the heat exchanger as the combustion gases are cooled from \( T_{\text{af}} \) to \( T_0 \). That is,
\[
W_{\text{rev}} = \dot{m}(h_i - h_e - T_0(s_i - s_e))
= \dot{m}C\left(T_{\text{af}} - T_0 - T_0\left(C\ln\frac{T_{\text{af}}}{T_0} - R\ln\frac{P_{\text{af}}}{P_0}\right)\right)
= \dot{m}C\left(T_{\text{af}} - T_0 - T_0C\ln\frac{T_{\text{af}}}{T_0}\right)
\]
which can be rearranged as
\[
W_{\text{rev}} = \dot{m}CT_0\left(\frac{T_{\text{af}}}{T_0} - 1 - \ln\frac{T_{\text{af}}}{T_0}\right) \quad \text{or} \quad W_{\text{rev}} = C\dot{m}\left(T_{\text{af}} - T_0 - 1 - \ln\frac{T_{\text{af}}}{T_0}\right) \quad (1)
\]
which is the desired result.

The effective flame temperature \( T_e \) can be determined from the requirement that a Carnot heat engine which receives the same amount of heat from a heat reservoir at constant temperature \( T_e \) produces the same amount of work. The amount of heat delivered to the heat engine above is
\[
\dot{Q}_H = \dot{m}(h_i - h_e) = \dot{m}C(T_{\text{af}} - T_0)
\]
A Carnot heat engine which receives this much heat at a constant temperature \( T_e \) will produce work in the amount of
\[
W = \dot{Q}_H\eta_{\text{th,Carnot}} = \dot{m}C(T_{\text{af}} - T_0)\left(1 - \frac{T_0}{T_e}\right) \quad (2)
\]
Setting equations (1) and (2) equal to each other yields
\[
\dot{m}CT_0\left(\frac{T_{\text{af}}}{T_0} - 1 - \ln\frac{T_{\text{af}}}{T_0}\right) = \dot{m}C(T_{\text{af}} - T_0)\left(1 - \frac{T_0}{T_e}\right)
\]
\[
T_{\text{af}} - T_0 - T_0\ln\frac{T_{\text{af}}}{T_0} = T_{\text{af}} - T_{\text{af}}\frac{T_0}{T_e} - T_0 + T_0\frac{T_0}{T_e}
\]
Simplifying and solving for \( T_e \), we obtain
\[
T_e = \frac{T_{\text{af}} - T_0}{\ln\left(\frac{T_{\text{af}}}{T_0}\right)}
\]
which is the desired relation.
The effect of the amount of air on the adiabatic flame temperature of liquid octane (C₈H₁₈) is to be investigated.

**Analysis** The problem is solved using EES, and the solution is given below.

Adiabatic Combustion of fuel CₙHₘ entering at Tₐₙₜ with Stoichiometric Air at T_air:

Reaction: \( C_xH_yO_z + \left(\frac{y}{4} + \frac{x-z}{2}\right) (\text{Theo}_{\text{air}}/100) (O_2 + 3.76 N_2) \)
\( \rightarrow xCO_2 + \left(\frac{y}{2}\right) H_2O + 3.76 \left(\frac{y}{4} + \frac{x-z}{2}\right) (\text{Theo}_{\text{air}}/100) N_2 + \left(\frac{y}{4} + \frac{x-z}{2}\right) (\text{Theo}_{\text{air}}/100 - 1) O_2 \)

"For theoretical oxygen, the complete combustion equation for CH₃OH is"
"CH₃OH + A_{th} O₂=1 CO₂+2 H₂O"
"1+2*A_{th}=1*2+2*1"\"theoretical O balance"

"Adiabatic, Incomplete Combustion of fuel CₙHₘ entering at Tₐₙₜ with Stoichiometric Air at T_air:

Reaction: \( C_xH_yO_z + \left(\frac{y}{4} + x-z/2\right) (\text{Theo}_{\text{air}}/100) (O_2 + 3.76 N_2) \)
\( \rightarrow (x-w)CO_2 +wCO + \left(\frac{y}{2}\right) H_2O + 3.76 \left(\frac{y}{4} + x-z/2\right) (\text{Theo}_{\text{air}}/100) N_2 + \left((x/4 + x - z/2) (\text{Theo}_{\text{air}}/100 - 1) + w/2\right)O_2 \)

"Tₚₚₒᵣᵣᵦᵢₛ the adiabatic combustion temperature, assuming no dissociation.
Theo_air is the % theoretical air."

"The initial guess value of Tₚᵢᵦᵢᵧᵦₛ = 450K."

Procedure \( \text{Fuel(Fuel$\$_T_fuel:x,y,z,h_fuel,Name$)} \)
"This procedure takes the fuel name and returns the moles of C and moles of H"

If fuel$='C2H2(g)' then
    x=2; y=2; z=0
    Name$='Acetylene'
    h_fuel = 226730
else
    If fuel$='C3H8(l)' then
        x=3; y=8; z=0
        Name$='Propane(liq)'
        h_fuel = -103850-15060
    else
        If fuel$='C8H18(l)' then
            x=8; y=18; z=0
            Name$='Octane(liq)'
            h_fuel = -249950
        else
            if fuel$='CH4(g)' then
                x=1; y=4; z=0
                Name$='Methane'
                h_fuel = enthalpy(CH4,T=T_fuel)
            else
                if fuel$='CH3OH(g)' then
                    x=1; y=4; z=1
                    Name$='Methyl alcohol'
                    h_fuel = -200670
                endif; endif; endif; endif; endif
end
Procedure \( \text{Moles(x,y,z,Th_air,A_{th}:w,MolO2,SolMeth$)} \)
ErrTh =\( \left(2*x + y/2 - z - x\right)/(2*A_{th}) \times 100 \)
IF Th_air >= 1 then
    SolMeth$ = '>= 100%, the solution assumes complete combustion.'
{MolCO = 0
MolCO2 = x}
w=0
MolO2 = A_th*(Th_air - 1)
GOTO 10
ELSE
w = 2*x + y/2 - z - 2*A_th*Th_air
IF w > x then
Call ERROR('The moles of CO2 are negative, the percent theoretical air must be >= xxx%','ErrTh')
Else
SolMeth$ = '< 100%, the solution assumes incomplete combustion with no O_2 in products.'
MolO2 = 0
endif; endif
10:
END
"Input data from the diagram window"
T_air = 298 [K]
Theo_air = 200 "%"
Fuel$='CH4(g)'
T_fuel = 298 [K]
Call Fuel(Fuel$,T_fuel;x,y,z,h_fuel,Name$)
A_th =x + y/4 - z/2
Th_air = Theo_air/100
Call Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)
HR=h_fuel+ (x+y/4-z/2) *(Theo_air/100) *enthalpy(O2,T=T_air)+3.76*(x+y/4-z/2) *(Theo_air/100)
*enthalpy(N2,T=T_air)
HP=HR "Adiabatic"
HP=(x-
w)*enthalpy(CO2,T=T_prod)+w*enthalpy(CO,T=T_prod)+(y/2)*enthalpy(H2O,T=T_prod)+3.76*(x+y/4-z/2)* (Theo_air/100)*enthalpy(N2,T=T_prod)+MolO2*enthalpy(O2,T=T_prod)
Moles_O2=MolO2
Moles_N2=3.76*(x+y/4-z/2) *(Theo_air/100)
Moles_CO=x-w
Moles_H2O=y/2

<table>
<thead>
<tr>
<th>Theo_air [%]</th>
<th>T_prod [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>2077</td>
</tr>
<tr>
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<tr>
<td>100</td>
<td>2396</td>
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<td>2122</td>
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<tr>
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<td>1827</td>
</tr>
<tr>
<td>200</td>
<td>1506</td>
</tr>
<tr>
<td>300</td>
<td>1153</td>
</tr>
<tr>
<td>500</td>
<td>840.1</td>
</tr>
<tr>
<td>800</td>
<td>648.4</td>
</tr>
</tbody>
</table>

Adiabatic Flame Temp. for C_8 H_{18} (liquid)
A general program is to be written to determine the heat transfer during the complete combustion of a hydrocarbon fuel C\textsubscript{n}H\textsubscript{m} at 25°C in a steady-flow combustion chamber when the percent of excess air and the temperatures of air and the products are specified.

**Analysis** The problem is solved using EES, and the solution is given below.

Steady-flow combustion of fuel C\textsubscript{n}H\textsubscript{m} entering at T\textsubscript{fuel} with Stoichiometric Air at T\textsubscript{air}:

Reaction: \[ CxHyOz + (x+y/4-z/2) (Theo\textsubscript{air}/100) (O2 + 3.76 N2) \rightarrow xCO2 + (y/2) H2O + 3.76 (x+y/4-z/2) (Theo\textsubscript{air}/100) N2 + (x+y/4-z/2) (Theo\textsubscript{air}/100 - 1) O2 \]

"For theoretical oxygen, the complete combustion equation for CH3OH is" 
"CH3OH + A\_th O2=1 CO2+2 H2O "
"1+ 2*A\_th=1*2+2*1""theoretical O balance"

"Steady-flow, Incomplete Combustion of fuel C\textsubscript{n}H\textsubscript{m} entering at T\textsubscript{fuel} with Stoichiometric Air at T\textsubscript{air}:

Reaction: \[ CxHyOz + (x+y/4-z/2) (Theo\textsubscript{air}/100) (O2 + 3.76 N2) \rightarrow (x-w)CO2 + wCO + (y/2) H2O + 3.76 (x+y/4-z/2) (Theo\textsubscript{air}/100) N2 + ((x+y/4-z/2) (Theo\textsubscript{air}/100 - 1) +w/2)O2 \]

"T\textsubscript{prod} is the product gas temperature, assuming no dissociation.
Theo\textsubscript{air} is the % theoretical air."

Procedure Fuel(Fuel$,T\_fuel;x,y,z,h\_fuel,Name$,MM)

"This procedure takes the fuel name and returns the moles of C and moles of H"

\[ \text{If fuel$='C2H2(g)' then} \]
\[ x=2; y=2; z=0 \]
\[ \text{Name$='Acetylene'} \]
\[ \text{h\_fuel} = 226730"Table A.26" \]
\[ \text{MM}=2*12+2*1 \]

\[ \text{else} \]
\[ \text{If fuel$='C3H8(l)' then} \]
\[ x=3; y=8; z=0 \]
\[ \text{Name$='Propane(liq)'} \]
\[ \text{h\_fuel} = -103850-15060"Tables A.26 and A.27" \]
\[ \text{MM}=\text{molarmass(C3H8)} \]

\[ \text{else} \]
\[ \text{If fuel$='C8H18(l)' then} \]
\[ x=8; y=18; z=0 \]
\[ \text{Name$='Octane(liq)'} \]
\[ \text{h\_fuel} = -249950"Table A.26" \]
\[ \text{MM}=8*12+18*1 \]

\[ \text{else if fuel$='CH4(g)' then} \]
\[ x=1; y=4; z=0 \]
\[ \text{Name$='Methane'} \]
\[ \text{h\_fuel} = \text{enthalpy(CH4,T=T\_fuel)} \]
\[ \text{MM}=\text{molarmass(CH4)} \]

\[ \text{else if fuel$='CH3OH(g)' then} \]
\[ x=1; y=4; z=1 \]
\[ \text{Name$='Methyl alcohol'} \]
\[ \text{h\_fuel} = -200670"Table A.26" \]
\[ \text{MM}=1*12+4*1+1*16 \]

end; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; endif; end
Procedure Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)

ErrTh = (2*x + y/2 - z - x)/(2*A_th)*100

IF Th_air >= 1 then

SolMeth$ = '>= 100%, the solution assumes complete combustion.'

w=0
MolO2 = A_th*(Th_air - 1)
GOTO 10
ELSE

w = 2*x + y/2 - z - 2*A_th*Th_air
IF w > x then

Call ERROR('The moles of CO2 are negative, the percent theoretical air must be >= xxxF3 %',ErrTh)

Else

SolMeth$ = '< 100%, the solution assumes incomplete combustion with no O_2 in products.'
MolO2 = 0
endif; endif

10:
END

{"Input data from the diagram window"
T_air = 298 [K]
Theo_air = 200 [%]
Fuel$='CH4(g)'
T_fuel = 298 [K]
Call Fuel(Fuel$,T_fuel:x,y,z,h_fuel,Name$,MM)
A_th = x + y/4 - z/2
Th_air = Theo_air/100
Call Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)
HR=h_fuel+ (x+y/4-z/2) *(Theo_air/100) *enthalpy(O2,T=T_air)+3.76*(x+y/4-z/2) *(Theo_air/100)
*enthalpy(N2,T=T_air)
HP=(x-w)*enthalpy(CO2,T=T_prod)+w*enthalpy(CO,T=T_prod)+(y/2)*enthalpy(H2O,T=T_prod)+3.76*(x
+y/4-z/2)* (Theo_air/100)*enthalpy(N2,T=T_prod)+MolO2*enthalpy(O2,T=T_prod)
Q_out=(HR-HP)/MM "kJ/kg_fuel"
Moles_O2=MolO2
Moles_N2=3.76*(x+y/4-z/2) *(Theo_air/100)
Moles_CO2=x-w
Moles_CO=w
Moles_H2O=y/2

SOLUTION for the sample calculation

A_th=5 fuel$='C3H8(l)'
HP=-149174 [kJ/kg]  HR=-119067 [kJ/kg]
h_fuel=-118910  MM=44.1 [kg/kmol]
Moles_CO=0.000  Moles_CO2=3.000
Moles_H2O=4  Moles_N2=28.200
Moles_O2=2.500  MolO2=2.5
Name$='Propane(liq)'  Q_out=682.8 [kJ/kg_fuel]
SolMeth$='>= 100%, the solution assumes complete combustion.'
Theo_air=150 [%]  Th_air=1.500
T_air=298 [K]  T_fuel=298 [K]
T_prod=1800 [K]  w=0  x=3  y=8  z=0
A general program is to be written to determine the adiabatic flame temperature during the complete combustion of a hydrocarbon fuel \( C_n H_m \) at 25\(^\circ\)C in a steady-flow combustion chamber when the percent of excess air and its temperature are specified.

**Analysis** The problem is solved using EES, and the solution is given below.

Adiabatic Combustion of fuel \( C_n H_m \) entering at \( T_{fuel} \) with Stoichiometric Air at \( T_{air} \):
Reaction:
\[
C_x H_y O_z + \left( \frac{y}{4} + \frac{x}{2} \right) \left( \frac{\text{Theo}_{air}}{100} \right) (O_2 + 3.76 \ N_2)
\rightarrow x CO_2 + \left( \frac{y}{2} \right) H_2O + 3.76 \ (\frac{y}{4} + \frac{x}{2} - \frac{z}{2}) \left( \frac{\text{Theo}_{air}}{100} \right) N_2 + \left( \frac{y}{4} + \frac{x}{2} - \frac{z}{2} \right) \left( \frac{\text{Theo}_{air}}{100} - 1 \right) O_2
\]

"For theoretical oxygen, the complete combustion equation for CH3OH is"
"CH3OH + A_{th} O_2=1 CO_2+2 H_2O "
"1+ 2*A_{th}=1*2+2*1""theoretical O balance"

Adiabatic, Incomplete Combustion of fuel \( C_n H_m \) entering at \( T_{fuel} \) with Stoichiometric Air at \( T_{air} \):
Reaction:
\[
C_x H_y O_z + \left( \frac{y}{4} + \frac{x}{2} \right) \left( \frac{\text{Theo}_{air}}{100} \right) (O_2 + 3.76 \ N_2)
\rightarrow \left( x-w \right) CO_2 + wCO + \left( \frac{y}{2} \right) H_2O + 3.76 \ (\frac{y}{4} + \frac{x}{2} - \frac{z}{2}) \left( \frac{\text{Theo}_{air}}{100} \right) N_2 + \left( \frac{y}{4} + \frac{x}{2} - \frac{z}{2} \right) \left( \frac{\text{Theo}_{air}}{100} - 1 \right) + w/2)O_2
\]

"\( T_{prod} \) is the adiabatic combustion temperature, assuming no dissociation.
\( \text{Theo}_{air} \) is the % theoretical air."
"The initial guess value of \( T_{prod} = 450K \)."

Procedure Fuel(Fuel$T\_fuel:x,y,z,h\_fuel,Name$)
"This procedure takes the fuel name and returns the moles of C and moles of H"
If fuel$='C2H2(g)' then
\[
x=2; y=2; z=0
\]
'Name$='acetylene'
\[
h\_fuel = 226730
\]
else If fuel$='C3H8(l)' then
\[
x=3; y=8; z=0
\]
'Name$='propane(liq)'
\[
h\_fuel = -103850-15060
\]
else If fuel$='C8H18(l)' then
\[
x=8; y=18; z=0
\]
'Name$='octane(liq)'
\[
h\_fuel = -249950
\]
else if fuel$='CH4(g)' then
\[
x=1; y=4; z=0
\]
'Name$='methane'
\[
h\_fuel = \text{enthalpy(CH4,T=T\_fuel)}
\]
else if fuel$='CH3OH(g)' then
\[
x=1; y=4; z=1
\]
'Name$='methyl alcohol'
\[
h\_fuel = -200670
\]
endif; endif; endif; endif; endif end

Procedure Moles(x,y,z,Th\_air,A\_th:w,MolO2,SolMeth$)
\[
\text{ErrTh}=(2*x + y/2 - x) / (2*A_{th}) \times 100
\]
IF Th_air >= 1 then
SolMeth$ = '>= 100%, the solution assumes complete combustion.'
{MolCO = 0
MolCO2 = x}
w=0
MolO2 = A_th*(Th_air - 1)
GOTO 10
ELSE
w = 2*x + y/2 - z - 2*A_th*Th_air
IF w > x then
Call ERROR("The moles of CO2 are negative, the percent theoretical air must be >= xxxF3
%",ErrTh)
Else
SolMeth$ = '< 100%, the solution assumes incomplete combustion with no O_2 in products.'
MolO2 = 0
endif; endif
10:
END

{"Input data from the diagram window"
T_air = 298 [K]
Theo_air = 200 [%]
Fuel$='CH4(g)'
T_fuel = 298 [K]
Call Fuel(Fuel$,T_fuel:x,y,z,h_fuel,Name$)
A_th = x + y/4 - z/2
Th_air = Theo_air/100
Call Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)
HR=h_fuel+ (x+y/4-z/2) *(Theo_air/100) *enthalpy(O2,T=T_air)+3.76*(x+y/4-z/2) *(Theo_air/100) 
*enthalpy(N2,T=T_air)
HP=HR "Adiabatic"
HP=(x-
w)*enthalpy(CO2,T=T_prod)+w*enthalpy(CO,T=T_prod)+(y/2)*enthalpy(H2O,T=T_prod)+3.76*(x +
y/4-z/2)* (Theo_air/100)*enthalpy(N2,T=T_prod)+MolO2*enthalpy(O2,T=T_prod)
Moles_O2=MolO2
Moles_N2=3.76*(x+y/4-z/2)* (Theo_air/100)
Moles_CO2=x-w
Moles_CO=w
Moles_H2O=y/2

SOLUTION for the sample calculation
A_th=5
fuel$='C3H8(l)'
HP=-119067 [kJ/kg]
HR=-119067 [kJ/kg]
Moles_CO2=3.000
Moles_H2O=4
Moles_N2=28.200
MolO2=2.5
SolMeth$='>= 100%, the solution assumes complete combustion.'
Theo_air=150 [%]
T_fuel=298 [K]
x=3
y=8
z=0
Th_air=1.500
T_air=298 [K]
**15-111 EES** The adiabatic flame temperature of the fuels CH₄(g), C₂H₂(g), CH₃OH(g), C₃H₈(g), and C₈H₁₈(l) is to be determined.

**Analysis** The problem is solved using EES, and the solution is given below.

Adiabatic Combustion of fuel CnHm entering at T_fuel with Stoichiometric Air at T_air:
Reaction:  CₓHᵧOᵦ  +  (y/4 + x-z/2) (Theo_air/100) (O₂ + 3.76 N₂)
<-->  xCO₂  +  (y/2) H₂O  +  3.76 (y/4 + x-z/2) (Theo_air/100) N₂ +  (y/4 + x-z/2)
(Theo_air/100 - 1) O₂"
(For theoretical oxygen, the complete combustion equation for CH₃OH is"
"CH3OH + A_th O₂=1 CO2+2 H₂O "
1+ 2*A_th=1*2+2*1"theoretical O balance"
"T_prod is the adiabatic combustion temperature, assuming no dissociation.
Theo_air is the % theoretical air. "
"The initial guess value of T_prod = 450K."

Procedure Fuel(Fuel$,T_fuel:x,y,z,h_fuel,Name$)
"This procedure takes the fuel name and returns the moles of C and moles of H"
If fuel$='C₂H₂(g)' then
  x=2; y=2; z=0
  Name$='acetylene'
  h_fuel = 226730"Table A.26"
else
If fuel$='C₃H₈(g)' then
  x=3; y=8; z=0
  Name$='propane'
  h_fuel = enthalpy(C₃H₈,T=T_fuel)
else
If fuel$='C₈H₁₈(l)' then
  x=8; y=18; z=0
  Name$='octane'
  h_fuel = -249950"Table A.26"
else
  if fuel$='CH₄(g)' then
    x=1; y=4; z=0
    Name$='methane'
    h_fuel = enthalpy(CH₄,T=T_fuel)
  else
    if fuel$='CH₃OH(g)' then
      x=1; y=4; z=1
      Name$='methyl alcohol'
      h_fuel = -200670"Table A.26"
  endif; endif; endif; endif; endif
end

("Input data from the diagram window"
T_air = 298 [K]
Theo_air = 200 [%]
Fuel$='CH₄(g)'
T_fuel = 298 [K]
Call Fuel(Fuel$,T_fuel:x,y,z,h_fuel,Name$)
A_th = y/4 + x-z/2
Th_air = Theo_air/100
HR=h_fuel+ (y/4 + x-z/2) *(Theo_air/100) *enthalpy(O₂,T=T_air)+3.76*(y/4 + x-z/2)
*(Theo_air/100) *enthalpy(N₂,T=T_air)
HP=HR "Adiabatic"
HP=x*enthalpy(CO2,T=T_prod)+(y/2)*enthalpy(H2O,T=T_prod)+3.76*(y/4 + x-z/2)*
(Theo_air/100)*enthalpy(N2,T=T_prod)+(y/4 + x-z/2) *(Theo_air/100 - 1)*enthalpy(O2,T=T_prod)
Moles_O2=(y/4 + x-z/2) *(Theo_air/100 - 1)
Moles_N2=3.76*(y/4 + x-z/2)* (Theo_air/100)
Moles_CO2=x
Moles_H2O=y/2
T[1]=T_prod; xa[1]=Theo_air "array variable are plotted in Plot Window 1"

SOLUTION for a sample calculation

A_th=1.5 fuel$='CH3OH(g)' HP=-200733 [kJ/kg]
HR=-200733 [kJ/kg] h_fuel=-200670 Moles_CO2=1
Moles_H2O=2 Moles_N2=11.280 Moles_O2=1.500
Moles_CO2=1
Name$='methyl alcohol' Theo_air=200 [%] Th_air=2
T_prod=1540 [K] x=1 xa[1]=200 [%]
y=4 z=1
15-112 EES The minimum percent of excess air that needs to be used for the fuels CH$_4$(g), C$_2$H$_4$(g), CH$_3$OH(g), C$_3$H$_8$(g), and C$_8$H$_{18}$(l) if the adiabatic flame temperature is not to exceed 1500 K is to be determined.

Analysis The problem is solved using EES, and the solution is given below.

Adiabatic Combustion of fuel C$_n$H$_m$ entering at $T_{fuel}$ with Stoichiometric Air at $T_{air}$:
Reaction: $C_xH_yO_z + (y/4 + x-z/2) (Theo\_air/100) (O_2 + 3.76 N_2)$
\[ \rightarrow xCO_2 + (y/2) H_2O + 3.76 (y/4 + x-z/2) (Theo\_air/100) N_2 + (y/4 + x-z/2) (Theo\_air/100 - 1) O_2 \]

("For theoretical oxygen, the complete combustion equation for CH$_3$OH is"
"CH$_3$OH + A\_th O$_2$=1 CO$_2$+2 H$_2$O  
1+ 2*A\_th=1*2+2*1"theoretical O balance")

"$T_{prod}$ is the adiabatic combustion temperature, assuming no dissociation.
Theo\_air is the % theoretical air."
"The initial guess value of $T_{prod}$ = 450K."

Procedure Fuel(Fuel$,T_{fuel}:x,y,z,h_fuel,Name$)
"This procedure takes the fuel name and returns the moles of C and moles of H"
If fuel$='C2H2(g)'$ then
x=2; y=2; z=0
Name$='acetylene'
else
If fuel$='C3H8(g)'$ then
x=3; y=8; z=0
Name$='propane'
else
If fuel$='C8H18(l)'$ then
x=8; y=18; z=0
Name$='octane'
else
if fuel$='CH4(g)'$ then
x=1; y=4; z=0
Name$='methane'
else
if fuel$='CH3OH(g)'$ then
x=1; y=4; z=1
Name$='methyl alcohol'
else
endif; endif; endif; endif; endif

end

("Input data from the diagram window"
$T_{air}$ = 298 [K]
Fuel$='CH4(g)'$
$T_{fuel}$ = 298 [K]

Excess\_air=Theo\_air - 100 "[%]"
Call Fuel(Fuel$,T_{fuel}:x,y,z,h_fuel,Name$
A\_th = y/4 + x-z/2

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\[ Th\_air = \frac{Theo\_air}{100} \]
\[ HR = h\_fuel + \frac{(y/4 + x - z/2)}{2} \times (Theo\_air/100) \times enthalpy(O_2,T=T\_air) + 3.76 \times \frac{(y/4 + x - z/2)}{2} \times (Theo\_air/100) \times enthalpy(N_2,T=T\_air) \]
\[ HP = HR \quad \text{"Adiabatic"} \]
\[ HP = x \times \text{enthalpy(CO}_2,T=T\_prod) + \frac{(y/2)}{2} \times \text{enthalpy(H}_2\text{O},T=T\_prod) + 3.76 \times \frac{(y/4 + x - z/2)}{2} \times (Theo\_air/100) \times \text{enthalpy(N}_2,T=T\_prod) + \frac{(y/4 + x - z/2)}{2} \times (Theo\_air/100 - 1) \times \text{enthalpy(O}_2,T=T\_prod) \]

Moles\_O_2 = \frac{(y/4 + x - z/2)}{2} \times (Theo\_air/100 - 1)
Moles\_N_2 = 3.76 \times \frac{(y/4 + x - z/2)}{2} \times (Theo\_air/100)
Moles\_CO_2 = x
Moles\_H_2O = \frac{y}{2}
T[1] = T\_prod; \ x[a][1] = Theo\_air

SOLUTION for a sample calculation

A\_th = 2.5 \hspace{1cm} \text{Excess\_air} = 156.251 \% \hspace{1cm} fuel$='C2H2(g)' \hspace{1cm} HP = 226596 \text{ [kJ/kg]}
HR = 226596 \text{ [kJ/kg]} \hspace{1cm} h\_fuel = 226730
Moles\_CO_2 = 2 \hspace{1cm} Moles\_H_2O = 1
Moles\_N_2 = 24.09 \hspace{1cm} Moles\_O_2 = 3.906
Name$='acetylene'$ \hspace{1cm} Theo\_air = 256.3 \% \hspace{1cm} \text{Th\_air} = 2.563 \hspace{1cm} T[1] = 1500 \text{ [K]}
T\_air = 298 \text{ [K]} \hspace{1cm} T\_fuel = 298 \text{ [K]}
T\_prod = 1500 \text{ [K]} \hspace{1cm} x = 2
xa[1] = 256.3 \hspace{1cm} y = 2
z = 0

PROPRIETARY MATERIAL. © 2006 The McGraw-Hill Companies, Inc. Limited distribution permitted only to teachers and educators for course preparation. If you are a student using this Manual, you are using it without permission.
The minimum percentages of excess air that need to be used for the fuels CH\(_4\)(g), C\(_2\)H\(_2\)(g), C\(_3\)H\(_8\)(g), and C\(_8\)H\(_{18}\)(l) FOR adiabatic flame temperatures of 1200 K, 1750 K, and 2000 K are to be determined.

**Analysis** The problem is solved using EES, and the solution is given below.

Adiabatic Combustion of fuel C\(_n\)H\(_m\) entering at T\(_{fuel}\) with Stoichiometric Air at T\(_{air}\):

Reaction: \(\text{C}_x\text{H}_y\text{O}_z + (\frac{y}{4} + \frac{x-z}{2}) \cdot \text{Theo}_{air}/100 \cdot (\text{O}_2 + 3.76 \text{N}_2) \rightarrow x\text{CO}_2 + (\frac{y}{2}) \text{H}_2\text{O} + 3.76 \cdot (\frac{y}{4} + \frac{x-z}{2}) \cdot \text{Theo}_{air}/100 \cdot \text{N}_2 + (\frac{y}{4} + \frac{x-z}{2}) \cdot (\text{Theo}_{air}/100 - 1) \text{O}_2\)

("For theoretical oxygen, the complete combustion equation for CH\(_3\)OH is"

"CH\(_3\)OH + A\(_th\) O\(_2\)=1 CO\(_2\)+2 H\(_2\)O"

1+ 2*A\(_th\)=1*2+2*1"theoretical O balance")

"T\(_{prod}\) is the adiabatic combustion temperature, assuming no dissociation.
Theo\(_{air}\) is the % theoretical air."

"The initial guess value of T\(_{prod}\) = 450K."

Procedure Fuel(Fuel\$,T\(_{fuel}\):x,y,z,h\(_{fuel}\),Name\$)

"This procedure takes the fuel name and returns the moles of C and moles of H"

If fuel\$='C\(_2\)H\(_2\)(g)' then

\(x=2; y=2; z=0\)

Name\$='acetylene'

h\(_{fuel}\) = 226730

else

If fuel\$='C\(_3\)H\(_8\)(g)' then

\(x=3; y=8; z=0\)

Name\$='propane'

h\(_{fuel}\) = enthalpy(C\(_3\)H\(_8\),T=T\(_{fuel}\))

else

If fuel\$='C\(_8\)H\(_{18}\)(l)' then

\(x=8; y=18; z=0\)

Name\$='octane'

h\(_{fuel}\) = -249950

else

if fuel\$='CH\(_4\)(g)' then

\(x=1; y=4; z=0\)

Name\$='methane'

h\(_{fuel}\) = enthalpy(CH\(_4\),T=T\(_{fuel}\))

else

if fuel\$='CH\(_3\)OH(g)' then

\(x=1; y=4; z=1\)

Name\$='methyl alcohol'

h\(_{fuel}\) = -200670

end if; end if; end if; endif

("Input data from the diagram window"

T\(_{air}\) = 298 [K]
Fuel\$='CH\(_4\)(g)'
T\(_{fuel}\) = 298 [K]

Excess\(_{air}\)=Theo\(_{air}\) - 100 [%]

Call Fuel(Fuel\$,T\(_{fuel}\):x,y,z,h\(_{fuel}\),Name\$)

A\(_th\) = \(\frac{y}{4} + \frac{x-z}{2}\)
\[
\begin{align*}
\text{Th\_air} &= \frac{\text{Theo\_air}}{100} \\
\text{HR} &= h\_fuel + \frac{(y/4 + x-z/2)}{\text{Theo\_air}/100} \cdot \text{enthalpy(O2,T=T\_air)} + 3.76 \cdot \frac{(y/4 + x-z/2)}{\text{Theo\_air}/100} \cdot \text{enthalpy(N2,T=T\_air)} \\
\text{HP} &= \text{HR \ "Adiabatic"} \\
\text{HP} &= x \cdot \text{enthalpy(CO2,T=T\_prod)} + \frac{(y/2)}{\text{enthalpy(H2O,T=T\_prod)}} + 3.76 \cdot \frac{(y/4 + x-z/2)}{\text{Theo\_air}/100} \cdot \text{enthalpy(N2,T=T\_prod)} + \frac{(y/4 + x-z/2)}{\text{Theo\_air}/100} \cdot \text{enthalpy(O2,T=T\_prod)} \\
\text{Moles\_O2} &= \frac{(y/4 + x-z/2)}{\text{Theo\_air}/100} - 1 \\
\text{Moles\_N2} &= 3.76 \cdot \frac{(y/4 + x-z/2)}{\text{Theo\_air}/100} \\
\text{Moles\_CO2} &= x \\
\text{Moles\_H2O} &= \frac{y}{2} \\
T[1] &= T\_prod; \ xa[1] = \text{Theo\_air}
\end{align*}
\]

**SOLUTION for a sample calculation**

\[
\begin{align*}
A\_th &= 5 \\
fuel$ &= 'C3H8(g)' \\
HR &= -103995 \ [kJ/kg] \\
h\_fuel &= -103858 \\
\text{Moles\_CO2} &= 3 \\
\text{Moles\_N2} &= 24.7 \\
\text{Moles\_O2} &= 1.570 \\
Name$ &= 'propane' \\
\text{Theo\_air} &= 131.4 \ [%] \\
\text{Th\_air} &= 1.314 \\
T\_air &= 298 \ [K] \\
T\_prod &= 2000 \ [K] \\
x &= 3 \\
y &= 8 \\
z &= 0
\end{align*}
\]
The adiabatic flame temperature of CH₄(g) is to be determined when both the fuel and the air enter the combustion chamber at 25°C for the cases of 0, 20, 40, 60, 80, 100, 200, 500, and 1000 percent excess air.

**Analysis** The problem is solved using EES, and the solution is given below.

Adiabatic Combustion of fuel CnHm entering at T_fuel with Stoichiometric Air at T_air:

Reaction: \( C_xH_yO_z + \left( \frac{y}{4} + \frac{x-z}{2} \right) \left( \text{Theo}_{air}/100 \right) (O_2 + 3.76 N_2) \rightarrow \) xCO₂ + \( \frac{y}{2} \) H₂O + 3.76 \( \left( \frac{y}{4} + \frac{x-z}{2} \right) \left( \text{Theo}_{air}/100 \right) \) N₂ + \( \left( \frac{y}{4} + \frac{x-z}{2} \right) \left( \text{Theo}_{air}/100 - 1 \right) O_2 \)

"For theoretical oxygen, the complete combustion equation for CH₃OH is"

"CH₃OH + A_th O₂=1 CO₂+2 H₂O "

"1+ 2*A_th=1*2+2*1" "theoretical O balance"

"Adiabatic, Incomplete Combustion of fuel CnHm entering at T_fuel with Stoichiometric Air at T_air:

Reaction: \( C_xH_yO_z + \left( \frac{y}{4} + \frac{x-z}{2} \right) \left( \text{Theo}_{air}/100 \right) (O_2 + 3.76 N_2) \rightarrow \) (x-w)CO₂ + wCO + \( \frac{y}{2} \) H₂O + 3.76 \( \left( \frac{y}{4} + \frac{x-z}{2} \right) \left( \text{Theo}_{air}/100 \right) \) N₂ + \( \left( \frac{y}{4} + \frac{x-z}{2} \right) \left( \text{Theo}_{air}/100 - 1 \right) + w/2 \) O₂"

"T Prod is the adiabatic combustion temperature, assuming no dissociation.

Theo_air is the % theoretical air."

"The initial guess value of T Prod = 450K ."

**Procedure** Fuel(Fuel$, T_fuel:x,y,z,h_fuel,Name$)

"This procedure takes the fuel name and returns the moles of C and moles of H"

If fuel$='C2H2(g)' then
  x=2; y=2; z=0
  Name$='acetylene'
  h_fuel = 226730
else
  If fuel$='C3H8(g)' then
    x=3; y=8; z=0
    Name$='propane'
    h_fuel = enthalpy(C3H8,T=T_fuel)
  else
    If fuel$='C8H18(l)' then
      x=8; y=18; z=0
      Name$='octane'
      h_fuel = -249950
    else
      if fuel$='CH4(g)' then
        x=1; y=4; z=0
        Name$='methane'
        h_fuel = enthalpy(CH4,T=T_fuel)
      else
        if fuel$='CH3OH(g)' then
          x=1; y=4; z=1
          Name$='methyl alcohol'
          h_fuel = -200670
        endif; endif; endif; endif; endif
end if; endif; endif; endif; endif

Procedure Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)

ErrTh =\((2x + y/2 - z - x)/(2*A_th)\)*100
IF Th_air >= 1 then
SolMeth$ = '>= 100%, the solution assumes complete combustion.'
{MolCO = 0  
MolCO2 = x}
w=0  
MolO2 = A_th*(Th_air - 1) 
GOTO 10  
ELSE  
w = 2*x + y/2 - z - 2*A_th*Th_air  
IF w > x then  
Call ERROR('The moles of CO2 are negative, the percent theoretical air must be >= xxxF3 %',ErrTh) 
Else  
SolMeth$ = '< 100%, the solution assumes incomplete combustion with no O_2 in products.' 
MolO2 = 0 
endif; endif  
10:  
END

{"Input data from the diagram window"  
T_air = 298 [K]  
Theo_air = 200 [%]  
Fuel$='CH4(g)'  
T_fuel = 298 [K]  
Call Fuel(Fuel$,T_fuel:x,y,z,h_fuel,Name$)  
A_th =x +  y/4 - z/2  
Th_air = Theo_air/100  
Call Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)  
HR=h_fuel+ (x+y/4-z/2) *(Theo_air/100) *enthalpy(O2,T=T_air)+3.76*(x+y/4-z/2) *(Theo_air/100)  
*enthalpy(N2,T=T_air)  
HP=HR  "Adiabatic"  
HP=(x-w)*enthalpy(CO2,T=T_prod)+w*enthalpy(CO,T=T_prod)+(y/2)*enthalpy(H2O,T=T_prod)+3.76*(x +y/4-z/2)* (Theo_air/100)*enthalpy(N2,T=T_prod)+MolO2*enthalpy(O2,T=T_prod)  
Moles_O2=MolO2  
Moles_N2=3.76*(x+y/4-z/2)* (Theo_air/100)  
Moles_CO2=x-w  
Moles_CO=w  
Moles_H2O=y/2

<table>
<thead>
<tr>
<th>Theo_air [%]</th>
<th>T_prod [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
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<tr>
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<tr>
<td>140</td>
<td>1872</td>
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<td>1480</td>
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<tr>
<td>300</td>
<td>1137</td>
</tr>
<tr>
<td>600</td>
<td>749.5</td>
</tr>
<tr>
<td>1100</td>
<td>553.5</td>
</tr>
</tbody>
</table>
15-115 EES  The rate of heat transfer is to be determined for the fuels \( \text{CH}_4(g) \), \( \text{C}_2\text{H}_2(g) \), \( \text{CH}_3\text{OH}(g) \), \( \text{C}_3\text{H}_8(g) \), and \( \text{C}_8\text{H}_{18}(l) \) when they are burned completely in a steady-flow combustion chamber with the theoretical amount of air.

Analysis  The problem is solved using EES, and the solution is given below.

Steady-floe combustion of fuel \( \text{CnHm} \) entering at \( T_{\text{fuel}} \) with Stoichiometric Air at \( T_{\text{air}} \):
Reaction:  \( \text{C}_x\text{H}_y\text{O}_z + (x+y/4-z/2) (\text{Theo}_{\text{air}}/100) (\text{O}_2 + 3.76 \text{N}_2) \rightarrow x\text{CO}_2 + (y/2) \text{H}_2\text{O} + 3.76 (x+y/4-z/2) (\text{Theo}_{\text{air}}/100) \text{N}_2 + (x+y/4-z/2) (\text{Theo}_{\text{air}}/100 - 1) \text{O}_2 \)
"For theoretical oxygen, the complete combustion equation for \( \text{CH}_3\text{OH} \) is"
"\( \text{CH}_3\text{OH} + A_{\text{th}} \text{O}_2 = 1 \text{CO}_2 + 2 \text{H}_2\text{O} \)"
"\( 1 + 2A_{\text{th}} = 1*2+2*1 \) "theoretical O balance"
"Steady-flow, Incomplete Combustion of fuel \( \text{CnHm} \) entering at \( T_{\text{fuel}} \) with Stoichiometric Air at \( T_{\text{air}} \):
Reaction:  \( \text{C}_x\text{H}_y\text{O}_z + (x+y/4-z/2) (\text{Theo}_{\text{air}}/100) (\text{O}_2 + 3.76 \text{N}_2) \rightarrow (x-w)\text{CO}_2 + w\text{CO} + (y/2) \text{H}_2\text{O} + 3.76 (x+y/4-z/2) (\text{Theo}_{\text{air}}/100) \text{N}_2 + ((x+y/4-z/2) (\text{Theo}_{\text{air}}/100 - 1) +w/2)\text{O}_2 \)
"\( T_{\text{prod}} \) is the product gas temperature, assuming no dissociation.
\( \text{Theo}_{\text{air}} \) is the % theoretical air."

Procedure Fuel(Fuel$,T_fuel;x,y,z,h_fuel,Name$,MM)
"This procedure takes the fuel name and returns the moles of C, H and O and molar mass"
If fuel$='\text{C}_2\text{H}_2(g)'$ then
   \( x=2; y=2; z=0 \)
   Name$='\text{acetylene}'
   h_fuel = 226730
   MM=2*12+2*1
else
If fuel$='\text{C}_3\text{H}_8(g)'$ then
   \( x=3; y=8; z=0 \)
   Name$='\text{propane}'
   h_fuel = enthalpy(C3H8,T=T_fuel)
   MM=molarmass(C3H8)
else
If fuel$='\text{C}_8\text{H}_{18}(l)'$ then
   \( x=8; y=18; z=0 \)
   Name$='\text{octane}'
   h_fuel = -249950
   MM=8*12+18*1
else
if fuel$='\text{CH}_4(g)'$ then
   \( x=1; y=4; z=0 \)
   Name$='\text{methane}'
   h_fuel = enthalpy(CH4,T=T_fuel)
   MM=molarmass(CH4)
else
if fuel$='\text{CH}_3\text{OH}(g)'$ then
   \( x=1; y=4; z=1 \)
   Name$='\text{methyl alcohol}'
   h_fuel = -200670
   MM=1*12+4*1+1*16
endif; endif; endif; endif; endif
endif; endif; endif; endif; endif
end

Procedure Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)
ErrTh = \frac{(2x + y/2 - z - x)}{(2A_{th})} * 100

IF Th\_air >= 1 then
SolMeth$ = '>= 100\%, the solution assumes complete combustion.'

w = 0
MolO2 = A_{th} * (Th\_air - 1)
GOTO 10
ELSE
w = 2x + y/2 - z - 2A_{th} * Th\_air
IF w > x then
Call ERROR('The moles of CO2 are negative, the percent theoretical air must be >= xxxF3 %', ErrTh)
Else
SolMeth$ = '< 100\%, the solution assumes incomplete combustion with no O_2 in products.'
MolO2 = 0
endif; endif
10:
END

"Input data from the diagram window"
m\_dot\_fuel = 0.1 [kg/s]
T\_air = 298 [K]
Theo\_air = 200 [%]
Fuel$='CH4(g)'
T\_fuel = 298 [K]
Call Fuel(Fuel$, T\_fuel, x, y, z, h\_fuel, Name$, MM)
A\_th = x + y/4 - z/2
Th\_air = Theo\_air/100
Call Moles(x, y, z, Th\_air, A\_th, w, MolO2, SolMeth$)
HR = h\_fuel + (x+y/4-z/2) * (Theo\_air/100) * enthalpy(O2, T=T\_air) + 3.76*(x+y/4-z/2) * (Theo\_air/100) * enthalpy(N2, T=T\_air)
HP = (x-w)*enthalpy(CO2, T=T\_prod) + w*enthalpy(CO, T=T\_prod) + (y/2)*enthalpy(H2O, T=T\_prod) + 3.76*(x+y/4-z/2) * (Theo\_air/100) * enthalpy(N2, T=T\_prod) + MolO2*enthalpy(O2, T=T\_prod)
HR = Q\_out + HP

"The heat transfer rate is:"
Q\_dot\_out = Q\_out/MM*m\_dot\_fuel "[kW]"
Moles\_O2 = MolO2
Moles\_N2 = 3.76*(x+y/4-z/2) * (Theo\_air/100)
Moles\_CO2 = x-w
Moles\_CO = w
Moles\_H2O = y/2

SOLUTION for a sample calculation

A\_th = 1.5
fuel$='CH3OH(g)'
HP = -604942 [kJ/kg]
HR = -200701 [kJ/kg]
Moles\_CO = 0.000
Moles\_CO2 = 1.000
Moles\_N2 = 5.640
Moles\_O2 = 0.000
m\_dot\_fuel = 1 [kg/s]
Name$='methyl alcohol'
Q\_out = 404241.1 [kJ/kmol\_fuel]
SolMeth$ = '>= 100\%, the solution assumes complete combustion.'
Theo\_air = 100 [%]
T\_air = 1.000
T\_fuel = 298 [K]
T\_prod = 1200 [K]
w = 0
x = 1
y = 4
z = 1

PROPRIETARY MATERIAL. © 2006 The McGraw-Hill Companies, Inc. Limited distribution permitted only to teachers and educators for course preparation. If you are a student using this Manual, you are using it without permission.
The rates of heat transfer are to be determined for the fuels CH\textsubscript{4}(g), C\textsubscript{2}H\textsubscript{2}(g), CH\textsubscript{3}OH(g), C\textsubscript{3}H\textsubscript{8}(g), and C\textsubscript{8}H\textsubscript{18}(l) when they are burned in a steady-flow combustion chamber with for 50, 100, and 200 percent excess air.

**Analysis** The problem is solved using EES, and the solution is given below.

Steady-flow combustion of fuel C\textsubscript{n}H\textsubscript{m} entering at T\textsubscript{fuel} with Stoichiometric Air at T\textsubscript{air}:

Reaction: C\textsubscript{x}H\textsubscript{y}O\textsubscript{z} + \(x+y/4-z/2\) (Theo\textsubscript{air}/100) (O\textsubscript{2} + 3.76 N\textsubscript{2})

\[\rightarrow xCO\textsubscript{2} + (y/2) H\textsubscript{2}O + 3.76 \cdot (x+y/4-z/2) (\text{Theo\textsubscript{air}/100}) \cdot N\text{2} + (x+y/4-z/2) (\text{Theo\textsubscript{air}/100} - 1) \cdot O\textsubscript{2}\]

"For theoretical oxygen, the complete combustion equation for CH\textsubscript{3}OH is"

"CH\textsubscript{3}OH + A\textsubscript{th} O\textsubscript{2}=1 \rightarrow CO\textsubscript{2}+2 H\textsubscript{2}O"

"1+ 2*A\textsubscript{th}=1*2+2*1" "theoretical O balance"

"Steady-flow, Incomplete Combustion of fuel C\textsubscript{n}H\textsubscript{m} entering at T\textsubscript{fuel} with Stoichiometric Air at T\textsubscript{air}:

Reaction: C\textsubscript{x}H\textsubscript{y}O\textsubscript{z} + \(x+y/4-z/2\) (Theo\textsubscript{air}/100) (O\textsubscript{2} + 3.76 N\textsubscript{2})

\[\rightarrow (x-w)CO\textsubscript{2} + wCO + (y/2) H\textsubscript{2}O + 3.76 \cdot (x+y/4-z/2) (\text{Theo\textsubscript{air}/100}) \cdot N\text{2} + ((x+y/4-z/2) (\text{Theo\textsubscript{air}/100} - 1) +w/2) O\textsubscript{2}\]

"T\textsubscript{prod} is the product gas temperature, assuming no dissociation.

Theo\textsubscript{air} is the % theoretical air." 

Procedure Fuel(Fuel$, T\textsubscript{fuel}; x, y, z, h\textsubscript{fuel}, Name$, MM)

"This procedure takes the fuel name and returns the moles of C and moles of H"

If fuel$='C2H2(g)' then

\[x=2; y=2; z=0\]

Name$='acetylene' \[h\textsubscript{fuel} = 226730\]

MM=2*12+2*1

else

If fuel$='C3H8(g)' then

\[x=3; y=8; z=0\]

Name$='propane' \[h\textsubscript{fuel} = \text{enthalpy(C3H8,T=T\textsubscript{fuel})}\]

MM=molarmass(C3H8)

else

If fuel$='C8H18(l)' then

\[x=8; y=18; z=0\]

Name$='octane' \[h\textsubscript{fuel} = -249950\]

MM=8*12+18*1

else

if fuel$='CH4(g)' then

\[x=1; y=4; z=0\]

Name$='methane' \[h\textsubscript{fuel} = \text{enthalpy(CH4,T=T\textsubscript{fuel})}\]

MM=molarmass(CH4)

else

if fuel$='CH3OH(g)' then

\[x=1; y=4; z=1\]

Name$='methyl alcohol' \[h\textsubscript{fuel} = -200670\]

MM=1*12+4*1+1*16

endif; endif; endif; endif; endif

Procedure Moles(x, y, z, Th\textsubscript{air}, A\textsubscript{th}; w, MolO2, SolMeth$)
`ErrTh = (2*x + y/2 - z - x)/(2*A_{th})*100
IF Th_{air} >= 1 then
  SolMeth$ = '>= 100\%, the solution assumes complete combustion.'
  w=0
  MoI02 = A_{th}*(Th_{air} - 1)
  GOTO 10
ELSE
  w = 2*x + y/2 - z - 2*A_{th}^*Th_{air}
  IF w > x then
    Call ERROR('The moles of CO2 are negative, the percent theoretical air must be >= xxxF3 
    %',ErrTh)
  Else
    SolMeth$ = '< 100\%, the solution assumes incomplete combustion with no O_2 in products.'
    MoI02 = 0
  endif; endif
10:
END

("Input data from the diagram window"

\begin{itemize}
  \item T_{air} = 298 [K]
  \item m_{dot_fuel}=1 [kg/s]
  \item Theo_{air} = 200 [%]
  \item Fuel$='CH4(g)'
  \item T_{fuel} = 298 [K]
\end{itemize}

Call Fuel(Fuel$,T_{fuel}:x,y,z,h_fuel,Name$,MM)
A_{th} = x + y/4 - z/2
Th_{air} = Theo_{air}/100
Call Moles(x,y,z,\text{Th}_{air},A_{th}:w,MoI02,SolMeth$)
HR=h_{fuel}+(x+y/4-z/2)\*\text{enthalpy(O2,T=T_{air})}+3.76\*(x+y/4-z/2)\*\text{enthalpy(T_{prod})}
HP=(x-w)\*\text{enthalpy(CO2,T=T_{prod})}+(y/2)\*\text{enthalpy(H2O,T=T_{prod})}+3.76\*(x+y/4-z/2)\*\text{enthalpy(N2,T=T_{prod})}+MoI02\*\text{enthalpy(O2,T=T_{prod})}
HR = Q_{out}+HP
"The heat transfer rate is:"
Q_{dot_out}=Q_{out}/MM*m_{dot_fuel}
Moles_{O2}=MoI02
Moles_{N2}=3.76\*(x+y/4-z/2)\*\text{Th_{air}/100}
Moles_{CO2}=x-w
Moles_{CO}=w
Moles_{H2O}=y/2

SOLUTION for a sample calculation

\begin{itemize}
  \item A_{th}=12.5
  \item fuel$='C8H18(l)' \quad \text{HP}=-1.641E+06 [kJ/kg]
  \item HR=-250472 [kJ/kg]
  \item Moles_{CO}=0.000
  \item Moles_{O2}=12.500
  \item m_{dot_fuel}=1 [kg/s]
  \item Q_{out}=1390433.6 [kJ/kmol_fuel]
  \item SolMeth$='>= 100\%, the solution assumes complete combustion.'
  \item Theo_{air}=200 [%]
  \item T_{air}=2.000
  \item T_{fuel}=298 [K]
  \item T_{prod}=1200 [K]
  \item x=8
  \item y=18
\end{itemize}
The fuel among CH$_4$(g), C$_2$H$_2$(g), C$_3$H$_6$(g), C$_3$H$_8$(g), and C$_8$H$_{18}$(l) that gives the highest temperature when burned completely in an adiabatic constant-volume chamber with the theoretical amount of air is to be determined.

**Analysis** The problem is solved using EES, and the solution is given below.

Adiabatic Combustion of fuel C$_n$H$_m$ with Stoichiometric Air at $T_{\text{fuel}}=T_{\text{air}}=T_{\text{reac}}$ in a constant volume, closed system:

Reaction: C$_x$H$_y$O$_z$ + $\left(\frac{x+y}{4}-\frac{z}{2}\right)$ (Theo$_{\text{air}}/100$) (O$_2$ + 3.76 N$_2$)  

$\rightarrow$ $x$CO$_2$ + $\left(\frac{y}{2}\right)$ H$_2$O + 3.76 $\left(\frac{x+y}{4}-\frac{z}{2}\right)$ (Theo$_{\text{air}}/100$) N$_2$ + $\left(\frac{x+y}{4}-\frac{z}{2}\right)$ (Theo$_{\text{air}}/100 - 1$) O$_2$

"For theoretical oxygen, the complete combustion equation for CH$_3$OH is"

"CH$_3$OH + A$_{\text{th}}$ O$_2$=1 CO$_2$+2 H$_2$O "

"1+ 2*A$_{\text{th}}$=1*2+2*1""theoretical O balance"

"Adiabatic, Incomplete Combustion of fuel C$_n$H$_m$ with Stoichiometric Air at $T_{\text{fuel}}=T_{\text{air}}=T_{\text{reac}}$ in a constant volume, closed system:

Reaction: C$_x$H$_y$O$_z$ + $\left(\frac{x+y}{4}-\frac{z}{2}\right)$ (Theo$_{\text{air}}/100$) (O$_2$ + 3.76 N$_2$)  

$\rightarrow$ $(x-w)$CO$_2$ +wCO + $\left(\frac{y}{2}\right)$ H$_2$O + 3.76 $\left(\frac{x+y}{4}-\frac{z}{2}\right)$ (Theo$_{\text{air}}/100$) N$_2$ + $\left(\frac{x+y}{4}-\frac{z}{2}\right)$ (Theo$_{\text{air}}/100 - 1$) +$\left(\frac{w}{2}\right)$O$_2$

"$T_{\text{prod}}$ is the adiabatic combustion temperature, assuming no dissociation. Theo$_{\text{air}}$ is the % theoretical air. "

"The initial guess value of $T_{\text{prod}} = 450K ."

Procedure Fuel(Fuel$,T_{\text{fuel}}:x,y,z,h_{\text{fuel}},Name$)

"This procedure takes the fuel name and returns the moles of C and moles of H"

If fuel$='C2H2(g)'$ then

\[
x=2; y=2; z=0
\]

Name$='acetylene' \quad h_{\text{fuel}} = 226730"Table A.26"

else

If fuel$='C3H8(g)'$ then

\[
x=3; y=8; z=0
\]

Name$='propane' \quad h_{\text{fuel}} = \text{enthalpy(C3H8,T=T_{\text{fuel}})}

else

If fuel$='C8H18(l)'$ then

\[
x=8; y=18; z=0
\]

Name$='octane' \quad h_{\text{fuel}} = -249950"Table A.26"

else

if fuel$='CH4(g)'$ then

\[
x=1; y=4; z=0
\]

Name$='methane' \quad h_{\text{fuel}} = \text{enthalpy(CH4,T=T_{\text{fuel}})}

else

if fuel$='CH3OH(g)'$ then

\[
x=1; y=4; z=1
\]

Name$='methyl alcohol' \quad h_{\text{fuel}} = -200670"Table A.26"

endif; endif; endif; endif; endif

END
Procedure Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)
ErrTh =((2*x + y/2 - z - x)/(2*A_th))^100
IF Th_air >= 1 then
SolMeth$ = '>= 100%, the solution assumes complete combustion.'
w=0
MolO2 = A_th*(Th_air - 1)
GOTO 10
ELSE
w = 2*x + y/2 - z - 2*A_th*Th_air
IF w > x then
Call ERROR("The moles of CO2 are negative, the percent theoretical air must be >= xxxxFF3%",'ErrTh)
Else
SolMeth$ = '< 100%, the solution assumes incomplete combustion with no O_2 in products.'
MolO2 = 0
endif; endif
10:
END

{"Input data from the diagram window"
Theo_air = 200 [%]
Fuel$='CH4(g)')
T_reac = 298 [K]
T_air = T_reac
T_fuel = T_reac
R_u = 8.314 [kJ/kmol-K]
Call Fuel(Fuel$,T_fuel:x,y,z,h_fuel,Name$)
A_th =x + y/4 - z/2
Th_air = Theo_air/100
Call Moles(x,y,z,Th_air,A_th:w,MolO2,SolMeth$)
UR=(h_fuel-R_u*T_fuel)+ (x+y/4-z/2) *(Theo_air/100) *(enthalpy(O2,T=T_air)-R_u*T_air)
UP=(x-w)*(enthalpy(CO2,T=T_prod)-R_u*T_prod)+w*(enthalpy(CO,T=T_prod)-R_u*T_prod)+3.76*(x+y/4-z/2)*
(Theo_air/100) *(enthalpy(N2,T=T_prod)-R_u*T_prod)+MolO2*(enthalpy(O2,T=T_prod)-R_u*T_prod)
UR =UP "Adiabatic, constant volume conservation of energy"
Moles_O2=MolO2
Moles_N2=3.76*(x+y/4-z/2)* (Theo_air/100)
Moles_CO2=x-w
Moles_CO=w
Moles_H2O=y/2
SOLUTION for CH4
A_th=2      fuel$='CH4(g)'   h_fuel=-74875
Moles_CO=0.000  Moles_CO2=1.000  Moles_H2O=2
Moles_N2=7.520  Moles_O2=0.000  MolO2=0
Name$='methane'  R_u=8.314 [kJ/kmol-K]
SolMeth$='>= 100%, the solution assumes complete combustion.'
Theo_air=100 [%]  Th_air=1.000  T_air=298 [K]
UP=-100981  UR=-100981  w=0
x=1  y=4  z=0

SOLUTION for C2H2
A_th=2.5    fuel$='C2H2(g)'   h_fuel=226730
Moles_CO=0.000  Moles_CO2=2.000  Moles_H2O=1
Moles_N2=9.400  Moles_O2=0.000  MolO2=0
Name$='acetylene'  R_u=8.314 [kJ/kmol-K]
SolMeth$='>= 100%, the solution assumes complete combustion.'
Theo_air=100 [%]  Th_air=1.000  T_air=298 [K]
UP=194717  UR=194717  w=0
x=2  y=2  z=0

SOLUTION for CH3OH
A_th=1.5    fuel$='CH3OH(g)'  h_fuel=-200670
Moles_CO=0.000  Moles_CO2=1.000  Moles_H2O=2
Moles_N2=5.640  Moles_O2=0.000  MolO2=0
Name$='methyl alcohol'  R_u=8.314 [kJ/kmol-K]
SolMeth$='>= 100%, the solution assumes complete combustion.'
Theo_air=100 [%]  Th_air=1.000  T_air=298 [K]
UP=-220869  UR=-220869  w=0
x=1  y=4  z=1

SOLUTION for C3H8
A_th=5      fuel$='C3H8(g)'   h_fuel=-103858
Moles_CO=0.000  Moles_CO2=3.000  Moles_H2O=4
Moles_N2=18.800  Moles_O2=0.000  MolO2=0
Name$='propane'  R_u=8.314 [kJ/kmol-K]
SolMeth$='>= 100%, the solution assumes complete combustion.'
Theo_air=100 [%]  Th_air=1.000  T_air=298 [K]
UP=-165406  UR=-165406  w=0
x=3  y=8  z=0

SOLUTION for C8H18
A_th=12.5    fuel$='C8H18(l)'   h_fuel=-249950
Moles_CO=0.000  Moles_CO2=8.000  Moles_H2O=9
Moles_N2=47.000  Moles_O2=0.000  MolO2=0
Name$='octane'  R_u=8.314 [kJ/kmol-K]
SolMeth$='>= 100%, the solution assumes complete combustion.'
Theo_air=100 [%]  Th_air=1.000  T_air=298 [K]
UP=-400104  UR=-400104  w=0
x=8  y=18  z=0
15-118 A fuel is burned with 90 percent theoretical air. This is equivalent to
(a) 10% excess air (b) 90% excess air (c) 10% deficiency of air
(d) 90% deficiency of air (e) stoichiometric amount of air

*Answer* (c) 10% deficiency of air

*Solution* Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
air_th=0.9
"air_th=air_access+1"
air_th=1-air_deficiency
```

15-119 Propane \( \text{C}_3\text{H}_8 \) is burned with 150 percent theoretical air. The air-fuel mass ratio for this combustion process is
(a) 5.3 (b) 10.5 (c) 15.7 (d) 23.4 (e) 39.3

*Answer* (d) 23.4

*Solution* Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
n_C=3
n_H=8
m_fuel=n_H*1+n_C*12
a_th=n_C+n_H/4
coeff=1.5  "coeff=1 for theoretical combustion, 1.5 for 50% excess air"
n_O2=coeff*a_th
n_N2=3.76*n_O2
m_air=n_O2*32+n_N2*28
AF=m_air/m_fuel
```

15-120 One kmol of methane (\( \text{CH}_4 \)) is burned with an unknown amount of air during a combustion process. If the combustion is complete and there are 2 kmol of free \( \text{O}_2 \) in the products, the air-fuel mass ratio is
(a) 34.3 (b) 17.2 (c) 19.0 (d) 14.9 (e) 12.1

*Answer* (a) 34.3

*Solution* Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
n_C=1
n_H=4
```

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m_fuel=n_H*1+n_C*12
a_th=n_C+n_H/4
(coeff-1)*a_th=2 "O2 balance: Coeff=1 for theoretical combustion, 1.5 for 50% excess air"
n_O2=coeff*a_th
n_N2=3.76*n_O2
m_air=n_O2*32+n_N2*28
AF=m_air/m_fuel

"Some Wrong Solutions with Common Mistakes:"
W1_AF=1/AF "Taking the inverse of AF"
W2_AF=n_O2+n_N2 "Finding air-fuel mole ratio"
W3_AF=AF/coeff "Ignoring excess air"

15-121 A fuel is burned steadily in a combustion chamber. The combustion temperature will be the highest except when
(a) the fuel is preheated.
(b) the fuel is burned with a deficiency of air.
(c) the air is dry.
(d) the combustion chamber is well insulated.
(e) the combustion is complete.

Answer (b) the fuel is burned with a deficiency of air.

15-122 An equimolar mixture of carbon dioxide and water vapor at 1 atm and 60°C enter a dehumidifying section where the entire water vapor is condensed and removed from the mixture, and the carbon dioxide leaves at 1 atm and 60°C. The entropy change of carbon dioxide in the dehumidifying section is
(a) –2.8 kJ/kg·K       (b) –0.13 kJ/kg·K       (c) 0       (d) 0.13 kJ/kg·K       (e) 2.8 kJ/kg·K

Answer (b) –0.13 kJ/kg·K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

Cp_CO2=0.846
R_CO2=0.1889
T1=60+273 "K"
T2=T1
P1= 1 "atm"
P2=1 "atm"
y1_CO2=0.5; P1_CO2=y1_CO2*P1
y2_CO2=1; P2_CO2=y2_CO2*P2
Ds_CO2=Cp_CO2*ln(T2/T1)-R_CO2*ln(P2_CO2/P1_CO2)

"Some Wrong Solutions with Common Mistakes:"
W1_Ds=0 "Assuming no entropy change"
W2_Ds=Cp_CO2*ln(T2/T1)-R_CO2*ln(P1_CO2/P2_CO2) "Using pressure fractions backwards"
**15-123** Methane \((\text{CH}_4)\) is burned completely with 80% excess air during a steady-flow combustion process. If both the reactants and the products are maintained at 25°C and 1 atm and the water in the products exists in the liquid form, the heat transfer from the combustion chamber per unit mass of methane is

(a) 890 MJ/kg  
(b) 802 MJ/kg  
(c) 75 MJ/kg  
(d) 56 MJ/kg  
(e) 50 MJ/kg

*Answer* (d) 56 MJ/kg

*Solution* Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

\[
\begin{align*}
T &= 25 \, ^\circ\text{C} \\
P &= 1 \, \text{atm} \\
\text{EXCESS} &= 0.8 \\
\text{"Heat transfer in this case is the HHV at room temperature,"} \\
\text{HHV}_{\text{CH}_4} &= 55.53 \, \text{MJ/kg} \\
\text{LHV}_{\text{CH}_4} &= 50.05 \, \text{MJ/kg} \\
\end{align*}
\]

"Some Wrong Solutions with Common Mistakes:"

- W1 \(Q = \text{LHV}_{\text{CH}_4}\) "Assuming lower heating value"
- W2 \(Q = \text{EXCESS} \times \text{HHV}_{\text{CH}_4}\) "Assuming \(Q\) to be proportional to excess air"

**15-124** The higher heating value of a hydrocarbon fuel \(C_nH_m\) with \(m = 8\) is given to be 1560 MJ/kmol of fuel. Then its lower heating value is

(a) 1384 MJ/kmol  
(b) 1208 MJ/kmol  
(c) 1402 MJ/kmol  
(d) 1540 MJ/kmol  
(e) 1550 MJ/kmol

*Answer* (a) 1384 MJ/kmol

*Solution* Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

\[
\begin{align*}
\text{HHV} &= 1560 \, \text{MJ/kmol fuel} \\
\text{h}_{\text{fg}} &= 2.4423 \, \text{MJ/kg, Enthalpy of vaporization of water at 25C} \\
n &= 8 \\
n_{\text{water}} &= n/2 \\
m_{\text{water}} &= n_{\text{water}} \times 18 \\
\text{LHV} &= \text{HHV} - \text{h}_{\text{fg}} \times m_{\text{water}}
\end{align*}
\]

"Some Wrong Solutions with Common Mistakes:"

- W1 \(\text{LHV} = \text{HHV} - \text{h}_{\text{fg}} \times n_{\text{water}}\) "Using mole numbers instead of mass"
- W2 \(\text{LHV} = \text{HHV} - \text{h}_{\text{fg}} \times m_{\text{water}}/2\) "Taking mole numbers of H2O to be \(m\) instead of \(m/2\"
- W3 \(\text{LHV} = \text{HHV} - \text{h}_{\text{fg}} \times n_{\text{water}}/2\) "Taking mole numbers of H2O to be \(m\) instead of \(m/2\), and using mole numbers"
Acetylene gas \((\text{C}_2\text{H}_2)\) is burned completely during a steady-flow combustion process. The fuel and the air enter the combustion chamber at 25°C, and the products leave at 1500 K. If the enthalpy of the products relative to the standard reference state is \(-404\) MJ/kmol of fuel, the heat transfer from the combustion chamber is
(a) 177 MJ/kmol  (b) 227 MJ/kmol  (c) 404 MJ/kmol  (d) 631 MJ/kmol  (e) 751 MJ/kmol

**Answer**  (d) 631 MJ/kmol

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

\[
\text{hf\_fuel}=226730/1000 \ "\text{MJ/kmol fuel}"
\]
\[
\text{H\_prod}=-404 \ "\text{MJ/kmol fuel}"
\]
\[
\text{H\_react}=\text{hf\_fuel}
\]
\[
\text{Q\_out}=\text{H\_react}-\text{H\_prod}
\]

"Some Wrong Solutions with Common Mistakes:"
W1\_Qout= -\text{H\_prod} "Taking Qout to be H\_prod"
W2\_Qout= \text{H\_react}+\text{H\_prod} "Adding enthalpies instead of subtracting them"

Benzene gas \((\text{C}_6\text{H}_6)\) is burned with 90 percent theoretical air during a steady-flow combustion process. The mole fraction of the CO in the products is
(a) 1.6%  (b) 4.4%  (c) 2.5%  (d) 10.0%  (e) 16.7%

**Answer**  (b) 4.4%

**Solution** Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

\[
n\_C=6
\]
\[
n\_H=6
\]
\[
a\_th=n\_C+n\_H/4
\]
\[
\text{coeff}=0.90 \ "\text{coeff}=1 for theoretical combustion, 1.5 for 50% excess air}"
\]
"Assuming all the H burns to H2O, the combustion equation is
\[
\text{C}_6\text{H}_6+\text{coeff}\ast a\_th(\text{O}_2+3.76\text{N}_2)\rightarrow (n\_\text{CO}_2)\ \text{CO}_2+(n\_\text{CO})\ \text{CO}+(n\_\text{H}_2\text{O})\ \text{H}_2\text{O}+(n\_\text{N}_2)\ \text{N}_2"
\]
\[
n\_\text{O}_2=\text{coeff}\ast a\_th
\]
\[
n\_\text{N}_2=3.76\ast n\_\text{O}_2
\]
\[
n\_\text{H}_2\text{O}=n\_\text{H}/2
\]
\[
n\_\text{CO}_2+n\_\text{CO}=n\_C
\]
\[
2\ast n\_\text{CO}_2+n\_\text{CO}+n\_\text{H}_2\text{O}=2\ast n\_\text{O}_2 \ "\text{Oxygen balance}"
\]
\[
n\_\text{prod}=n\_\text{CO}_2+n\_\text{CO}+n\_\text{H}_2\text{O}+n\_\text{N}_2 \ "\text{Total mole numbers of product gases}"
\]
\[
y\_\text{CO}=n\_\text{CO}/n\_\text{prod} \ "\text{mole fraction of CO in product gases}"
\]

"Some Wrong Solutions with Common Mistakes:"
W1\_y\text{CO}=n\_\text{CO}/n\_\text{prod}; n\_\text{prod}=n\_\text{CO}_2+n\_\text{CO}+n\_\text{H}_2\text{O} "\text{Not including N}_2\ \text{in n\_prod}"
W2\_y\text{CO}=(n\_\text{CO}_2+n\_\text{CO})/n\_\text{prod} "\text{Using both CO and CO}_2\ \text{in calculations}"

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A fuel is burned during a steady-flow combustion process. Heat is lost to the surroundings at 300 K at a rate of 1120 kW. The entropy of the reactants entering per unit time is 17 kW/K and that of the products is 15 kW/K. The total rate of exergy destruction during this combustion process is

(a) 520 kW  
(b) 600 kW  
(c) 1120 kW  
(d) 340 kW  
(e) 739 kW

Answer (a) 520 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

To=300 "K"
Q_out=1120 "kW"
S_react=17 "kW/K"
S_prod= 15 "kW/K"
S_react-S_prod-Q_out/To+S_gen=0 "Entropy balance for steady state operation, Sin-Sout+Sgen=0"
X_dest=To*S_gen

"Some Wrong Solutions with Common Mistakes:"
W1_Xdest=S_gen "Taking Sgen as exergy destruction"
W2_Xdest=To*S_gen1; S_react-S_prod-S_gen1=0 "Ignoring Q_out/To"

15-128 ··· 15-133 Design and Essay Problems

15-129a Constant-volume vessels that store flammable gases are to be designed to withstand the rising pressures in case of an explosion. The safe design pressures for (a) acetylene, (b) propane, and (c) n-octane are to be determined for storage pressures slightly above the atmospheric pressure.

Analysis (a) The final temperature (and pressure) in the tank will be highest when the combustion is complete, adiabatic, and stoichiometric. In addition, we assume the atmospheric pressure to be 100 kPa and the initial temperature in the tank to be 25°C. Then the initial pressure of the air-fuel mixture in the tank becomes 125 kPa.

The combustion equation of C$_2$H$_2$(g) with stoichiometric amount of air is

\[ C_2H_2 + a_{th}(O_2 + 3.76N_2) \rightarrow 2CO_2 + H_2O + 3.76a_{th}N_2 \]

where $a_{th}$ is the stoichiometric coefficient and is determined from the O$_2$ balance,

\[ a_{th} = 2 + 0.5 \rightarrow a_{th} = 2.5 \]

Thus,

\[ C_2H_2 + 2.5(O_2 + 3.76N_2) \rightarrow 2CO_2 + H_2O + 9.40N_2 \]

The final temperature in the tank is determined from the energy balance relation $E_{in} - E_{out} = \Delta E_{system}$ for reacting closed systems under adiabatic conditions ($Q = 0$) with no work interactions ($W = 0$),

\[ 0 = \sum N_P (\bar{h}^*_j + \bar{h} - \bar{h}^* - P\bar{v})_P - \sum N_R (\bar{h}^*_j + \bar{h} - \bar{h}^* - P\bar{v})_R \]
Assuming both the reactants and the products to behave as ideal gases, all the internal energy and enthalpies depend on temperature only, and the $P \mathcal{V}$ terms in this equation can be replaced by $R_u T$. It yields

$$\sum N_p (\tilde{h}_f^n - \tilde{h}_{298K} - R_u T) = \sum N_r (\tilde{h}_f^n - R_u T)$$

since the reactants are at the standard reference temperature of 25°C. From the tables,

<table>
<thead>
<tr>
<th>Substance</th>
<th>$\tilde{h}_f^n$ kJ/kmol</th>
<th>$\tilde{h}_{298K}$ kJ/kmol</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_2$H$_2$</td>
<td>226,730</td>
<td>---</td>
</tr>
<tr>
<td>O$_2$</td>
<td>0</td>
<td>8682</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0</td>
<td>8669</td>
</tr>
<tr>
<td>H$_2$O (g)</td>
<td>-241,820</td>
<td>9904</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>-393,520</td>
<td>9364</td>
</tr>
</tbody>
</table>

Thus,

$$2(\tilde{h}_{CO_2} + \tilde{h}_{H_2O} + 9.40\tilde{h}_{N_2} - 103.094 \times T_p) = 1,333,750 \text{ kJ}$$

The temperature of the product gases is obtained from a trial and error solution,

At 3200 K:

$$2\tilde{h}_{CO_2} + \tilde{h}_{H_2O} + 9.40\tilde{h}_{N_2} - 103.094 \times T_p = (2\times 174,695) + (1\times 174,695) + (9.40\times 108,830) - (103.094\times 3200)$$

$$= 1,189,948 \text{ kJ} \quad (\text{Lower than } 1,333,750 \text{ kJ})$$

At 3250 K:

$$2\tilde{h}_{CO_2} + \tilde{h}_{H_2O} + 9.40\tilde{h}_{N_2} - 103.094 \times T_p = (2\times 177,822) + (1\times 150,272) + (9.40\times 110,690) - (103.094\times 3250)$$

$$= 1,211,347 \text{ kJ} \quad (\text{Lower than } 1,333,750 \text{ kJ})$$

By extrapolation, $T_p = 3536 \text{ K}$

Treating both the reactants and the products as ideal gases, the final (maximum) pressure that can occur in the combustion chamber is determined to be

$$P_1 \mathcal{V} = \frac{N_1 R_u T_1}{N_2 R_u T_2} \rightarrow P_2 = \frac{N_2 T_2}{N_1 T_1} P_1 = \frac{(12.40 \text{ kmol})(3536 \text{ K})}{(12.90 \text{ kmol})(298 \text{ K})} = 1426 \text{ kPa}$$

Then the pressure the tank must be designed for in order to meet the requirements of the code is $P = 4 \times 1426 \text{ kPa} = 5704 \text{ kPa}$
The final temperature (and pressure) in the tank will be highest when the combustion is complete, adiabatic, and stoichiometric. In addition, we assume the atmospheric pressure to be 100 kPa and the initial temperature in the tank to be 25°C. Then the initial pressure of the air-fuel mixture in the tank becomes 125 kPa.

The combustion equation of \( \text{C}_3\text{H}_8(g) \) with stoichiometric amount of air is

\[
\text{C}_3\text{H}_8 + a_{th}(\text{O}_2 + 3.76\text{N}_2) \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} + 3.76a_{th}\text{N}_2
\]

where \( a_{th} \) is the stoichiometric coefficient and is determined from the \( \text{O}_2 \) balance,

\[
a_{th} = 3 + 2 \rightarrow a_{th} = 5
\]

Thus,

\[
\text{C}_3\text{H}_8 + 5(\text{O}_2 + 3.76\text{N}_2) \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} + 18.80\text{N}_2
\]

The final temperature in the tank is determined from the energy balance relation for reacting closed systems under adiabatic conditions (\( Q = 0 \)) with no work interactions (\( W = 0 \)),

\[
0 = \sum N_p(\bar{h}_p^* + \bar{h}_f^* - P\bar{\varphi})_p - \sum N_R(\bar{h}_p^* + \bar{h}_f^* - P\bar{\varphi})_R
\]

Assuming both the reactants and the products to behave as ideal gases, all the internal energy and enthalpies depend on temperature only, and the \( P\bar{\varphi} \) terms in this equation can be replaced by \( R_u T \). It yields

\[
\sum N_p(\bar{h}_p^* + \bar{h}_f^* - \bar{h}_{298K}^* - R_u T)_p = \sum N_R(\bar{h}_p^* - R_u T)_R
\]

since the reactants are at the standard reference temperature of 25°C. From the tables,

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \bar{h}_f^* ) kJ/kmol</th>
<th>( \bar{h}_{298K}^* ) kJ/kmol</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{C}_3\text{H}_8 )</td>
<td>-103,850</td>
<td>---</td>
</tr>
<tr>
<td>( \text{O}_2 )</td>
<td>0</td>
<td>8682</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>0</td>
<td>8669</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} (g) )</td>
<td>-241,820</td>
<td>9904</td>
</tr>
<tr>
<td>( \text{CO}_2 )</td>
<td>-393,520</td>
<td>9364</td>
</tr>
</tbody>
</table>

Thus,

\[
(3)(-393,520 + \bar{h}_{\text{CO}_2} - 9364 - 8.314 \times T_p) + (4)(-241,820 + \bar{h}_{\text{H}_2\text{O}} - 9904 - 8.314 \times T_p) + (18.80)(0 + \bar{h}_{\text{N}_2} - 8669 - 8.314 \times T_p)
\]

\[
= (1)(-103,850 - 8.314 \times 298) + (5)(0 - 8.314 \times 298) + (18.80)(0 - 8.314 \times 298)
\]

It yields

\[
3\bar{h}_{\text{CO}_2} + 4\bar{h}_{\text{H}_2\text{O}} + 18.80\bar{h}_{\text{N}_2} - 214.50 \times T_p = 2,213,231 \text{ kJ}
\]

The temperature of the product gases is obtained from a trial and error solution,

At 2950 K:

\[
3\bar{h}_{\text{CO}_2} + 4\bar{h}_{\text{H}_2\text{O}} + 18.80\bar{h}_{\text{N}_2} - 214.50 \times T_p = (3)(159,117) + (4)(133,486) + (18.80)(99,556) - (214.50)(2950)
\]

\[
= 2,250,173 \text{ kJ (Higher than 2,213,231 kJ)}
\]

At 2900 K:

\[
3\bar{h}_{\text{CO}_2} + 4\bar{h}_{\text{H}_2\text{O}} + 18.80\bar{h}_{\text{N}_2} - 214.50 \times T_p = (3)(156,009) + (4)(130,717) + (18.80)(97,705) - (214.50)(2900)
\]

\[
= 2,205,699 \text{ kJ (Lower than 2,213,231 kJ)}
\]

By interpolation, \( T_p = 2908 \text{ K} \)

Treating both the reactants and the products as ideal gases, the final (maximum) pressure that can occur in the combustion chamber is determined to be

\[
\frac{P_1\bar{\varphi}}{P_2\bar{\varphi}} = \frac{N_1 R_u T_1}{N_2 R_u T_2} \rightarrow P_2 = \frac{N_2 R_u T_2}{N_1 R_u T_1} \frac{P_1}{(25.80 \text{ kJ})(2908 \text{ K})} (125 \text{ kPa}) = 1269 \text{ kPa}
\]

Then the pressure the tank must be designed for in order to meet the requirements of the code is

\[
P = (4)(1269 \text{ kPa}) = 5076 \text{ kPa}
\]
The final temperature (and pressure) in the tank will be highest when the combustion is complete, adiabatic, and stoichiometric. In addition, we assume the atmospheric pressure to be 100 kPa and the initial temperature in the tank to be 25°C. Then the initial pressure of the air-fuel mixture in the tank becomes 125 kPa.

The combustion equation of C₈H₁₈(g) with stoichiometric amount of air is

\[ C₈H₁₈ + aₘ(O₂ + 3.76N₂) \rightarrow 8CO₂ + 9H₂O + 3.76aₘN₂ \]

where \( aₘ \) is the stoichiometric coefficient and is determined from the O₂ balance,

\[ aₘ = 8 + 4.5 \rightarrow aₘ = 12.5 \]

Thus,

\[ C₈H₁₈ + 12.5(O₂ + 3.76N₂) \rightarrow 8CO₂ + 9H₂O + 47.0N₂ \]

The final temperature in the tank is determined from the energy balance relation for reacting closed systems under adiabatic conditions (\( Q = 0 \)) with no work interactions (\( W = 0 \)),

\[ 0 = \sum N_p (\tilde{h}_f^p + \tilde{h}_r - \tilde{h}_r + P\tilde{\varphi})_p - \sum N_R (\tilde{h}_f^p + \tilde{h}_r - \tilde{h}_r + P\tilde{\varphi})_R \]

Assuming both the reactants and the products to behave as ideal gases, all the internal energy and enthalpies depend on temperature only, and the \( P\tilde{\varphi} \) terms in this equation can be replaced by \( R_uT \). It yields

\[ \sum N_p (\tilde{h}_f^p + \tilde{h}_r - \tilde{h}_{298K} - R_uT)_p = \sum N_R (\tilde{h}_f^p - R_uT)_R \]

since the reactants are at the standard reference temperature of 25°C. From the tables,

<table>
<thead>
<tr>
<th>Substance</th>
<th>( \tilde{h}_f^p )</th>
<th>( \tilde{h}_{298K} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₈H₁₈</td>
<td>-208,450</td>
<td>---</td>
</tr>
<tr>
<td>O₂</td>
<td>0</td>
<td>8682</td>
</tr>
<tr>
<td>N₂</td>
<td>0</td>
<td>8669</td>
</tr>
<tr>
<td>H₂O (g)</td>
<td>-241,820</td>
<td>9904</td>
</tr>
<tr>
<td>CO₂</td>
<td>-393,520</td>
<td>9364</td>
</tr>
</tbody>
</table>

Thus,

\[ (8)\left[-393,520 + \tilde{h}_{CO₂} - 9364 - 8.314 \times T_p\right] + (9)\left[-241,820 + \tilde{h}_{H₂O} - 9904 - 8.314 \times T_p\right] + (47.0)\left[0 + \tilde{h}_{N₂} - 8669 - 8.314 \times T_p\right] = \left[1\right]\left[-208,450 - 8.314 \times 298\right] + \left[12.5\right]\left[0 - 8.314 \times 298\right] + \left[47.0\right]\left[0 - 8.314 \times 298\right] \]

It yields

\[ 8\tilde{h}_{CO₂} + 9\tilde{h}_{H₂O} + 47.0\tilde{h}_{N₂} - 532.10 \times T_p = 5,537,688 \text{ kJ} \]

The temperature of the product gases is obtained from a trial and error solution,

At 2950 K:

\[ 8\tilde{h}_{CO₂} + 9\tilde{h}_{H₂O} + 47.0\tilde{h}_{N₂} - 532.10 \times T_p = (8)(159,117) + (9)(133,486) + (47.0)(99,556) - (532.10)(2950) = 5,583,747 \text{ kJ} \text{ (Higher than 5,534,220 kJ)} \]

At 2900 K:

\[ 8\tilde{h}_{CO₂} + 9\tilde{h}_{H₂O} + 47.0\tilde{h}_{N₂} - 532.10 \times T_p = (8)(156,009) + (9)(130,717) + (47.0)(97,705) - (532.10)(2900) = 5,473,570 \text{ kJ} \text{ (Lower than 5,534,220 kJ)} \]

By interpolation,

\[ T_p = 2929 \text{ K} \]

Treating both the reactants and the products as ideal gases, the final (maximum) pressure that can occur in the combustion chamber is determined to be

\[ \frac{P_1\tilde{\varphi}}{P_2\tilde{\varphi}} = \frac{N_1R_uT_1}{N_2R_uT_2} \rightarrow P_2 = \frac{N_2T_2}{N_1T_1} P_1 = \frac{64.0 \text{ kmol}(2929 \text{ K})}{60.5 \text{ kmol}(298 \text{ K})}(125 \text{ kPa}) = 1300 \text{ kPa} \]

Then the pressure the tank must be designed for in order to meet the requirements of the code is

\[ P = (4)(1300 \text{ kPa}) = 5200 \text{ kPa} \]
A certain industrial process generates a liquid solution of ethanol and water as the waste product. The solution is to be burned using methane. A combustion process is to be developed to accomplish this incineration process with minimum amount of methane.

**Analysis** The mass flow rate of the liquid ethanol-water solution is given to be 10 kg/s. Considering that the mass fraction of ethanol in the solution is 0.2,

\[ m_{\text{ethanol}} = (0.2)(10 \text{ kg/s}) = 2 \text{ kg/s} \]
\[ m_{\text{water}} = (0.8)(10 \text{ kg/s}) = 8 \text{ kg/s} \]

Noting that the molar masses \( M_{\text{ethanol}} = 46 \) and \( M_{\text{water}} = 18 \text{ kg/kmol} \) and that mole numbers \( N = m/M \), the mole flow rates become

\[ \dot{N}_{\text{ethanol}} = \frac{m_{\text{ethanol}}}{M_{\text{ethanol}}} = \frac{2 \text{ kg/s}}{46 \text{ kg/kmol}} = 0.04348 \text{ kmol/s} \]
\[ \dot{N}_{\text{water}} = \frac{m_{\text{water}}}{M_{\text{water}}} = \frac{8 \text{ kg/s}}{18 \text{ kg/kmol}} = 0.44444 \text{ kmol/s} \]

Note that

\[ \frac{\dot{N}_{\text{water}}}{\dot{N}_{\text{ethanol}}} = \frac{0.44444}{0.04348} = 10.222 \text{ kmol } H_2O/\text{kmol } C_2H_5OH \]

That is, 10.222 moles of liquid water is present in the solution for each mole of ethanol.

Assuming complete combustion, the combustion equation of \( C_2H_5OH(l) \) with stoichiometric amount of air is

\[ C_2H_5OH(l) + a_{th}(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 3.76a_{th}N_2 \]

where \( a_{th} \) is the stoichiometric coefficient and is determined from the \( O_2 \) balance,

\[ 1 + 2a_{th} = 4 + 3 \quad \rightarrow \quad a_{th} = 3 \]

Thus,

\[ C_2H_5OH(l) + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 11.28N_2 \]

Noting that 10.222 kmol of liquid water accompanies each kmol of ethanol, the actual combustion equation can be written as

\[ C_2H_5OH(l) + 3(O_2 + 3.76N_2) + 10.222H_2O(l) \rightarrow 2CO_2 + 3H_2O(g) + 11.28N_2 + 10.222H_2O(l) \]

The heat transfer for this combustion process is determined from the steady-flow energy balance equation with \( W = 0 \),

\[ Q = \sum N_p \left( h_j^p + h - h^* \right)_p - \sum N_R \left( h_j^R + h - h^* \right)_R \]

Assuming the air and the combustion products to be ideal gases, we have \( h = h(T) \). We assume all the reactants to enter the combustion chamber at the standard reference temperature of 25°C. Furthermore, we assume the products to leave the combustion chamber at 1400 K which is a little over the required temperature of 1100°C. From the tables,
Thus,

\[ Q = (2)(-393,520 + 65,271 - 9364) + (3)(-241,820 + 53,351 - 9904) + (11.28)(0 + 43,605 - 8669)(-277,690) - 0 - 0 + (10.222)(-241,820 + 53,351 - 9904) - (10.222)(-285,830) \]

\[ = 295,409 \text{ kJ/kmol of C}_2\text{H}_5\text{OH} \]

The positive sign indicates that 295,409 kJ of heat must be supplied to the combustion chamber from another source (such as burning methane) to ensure that the combustion products will leave at the desired temperature of 1400 K. Then the rate of heat transfer required for a mole flow rate of 0.04348 kmol C\textsubscript{2}H\textsubscript{5}OH/s CO becomes

\[ \dot{Q} = \dot{N}Q = (0.04348 \text{ kmol/s})(295,409 \text{ kJ/kmol}) = 12,844 \text{ kJ/s} \]

Assuming complete combustion, the combustion equation of CH\textsubscript{4}(g) with stoichiometric amount of air is

\[ \text{CH}_4 + a_{th}(\text{O}_2 + 3.76\text{N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 3.76a_{th}\text{N}_2 \]

where \(a_{th}\) is the stoichiometric coefficient and is determined from the O\textsubscript{2} balance,

\[ a_{th} = 1 + 1 \quad a_{th} = 2 \]

Thus,

\[ \text{CH}_4 + 2(\text{O}_2 + 3.76\text{N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 7.52\text{N}_2 \]

The heat transfer for this combustion process is determined from the steady-flow energy balance \(E_{in} - E_{out} = \Delta E_{\text{system}}\) equation as shown above under the same assumptions and using the same mini table:

\[ Q = (1)(-393,520 + 65,271 - 9364) + (2)(-241,820 + 53,351 - 9904) + (7.52)(0 + 43,605 - 8669)(-74,850) - 0 - 0 \]

\[ = -396,790 \text{ kJ/kmol of CH}_4 \]

That is, 396,790 kJ of heat is supplied to the combustion chamber for each kmol of methane burned. To supply heat at the required rate of 12,844 kJ/s, we must burn methane at a rate of

\[ \dot{N}_{\text{CH}_4} = \dot{Q} \rightleftharpoons Q = \frac{12,844 \text{ kJ/s}}{396,790 \text{ kJ/kmol}} = 0.03237 \text{ kmolCH}_4/\text{s} \]

or,

\[ \dot{m}_{\text{CH}_4} = M_{\text{CH}_4} \dot{N}_{\text{CH}_4} = (16 \text{ kg/kmol})(0.03237 \text{ kmolCH}_4/\text{s}) = 0.5179 \text{ kg/s} \]

Therefore, we must supply methane to the combustion chamber at a minimum rate 0.5179 kg/s in order to maintain the temperature of the combustion chamber above 1400 K.