13-1-1 [OMT] Methane is burned with the theoretical amount of air during a combustion process. Assuming complete combustion, determine the air-fuel ratio on (a) mass basis, (b) mole basis, and (c) volume basis.

SOLUTION:

The chemical balance equation:

$$CH_4 + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

C: 1 = b
H: 4 = 2c $\Rightarrow$ c = 2
O: 2a = 2b + c $\Rightarrow$ 2a = 2 + 2 $\Rightarrow$ a = 2
N: 3.76a = d $\Rightarrow$ d = 7.72

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

(a) Mass basis:

$$AF = \overline{AF} = \frac{\bar{M}_{air}}{\bar{M}_F}$$

$$AF = 9.52 \frac{\frac{32 + 3.76 \cdot 28}{4.76}}{16} = 9.52 \frac{28.84}{16} = (9.52)(1.8) = 17.16$$

(b) Mole basis:

$$AF = \frac{\eta_{fuel}}{\eta_{air}} = \frac{2(4.76)}{1} = 9.52$$

(c) Volume basis:

$$\overline{AF} = 2 + 2\,(3.76) = 9.52$$

TEST Verification: Use the n-IG non-premixed open-steady combustion TESTcalc to verify the results.

13-1-2 [OMD] Acetylene (C_2H_2) is burned with the stoichiometric amount of air during a combustion process. Assuming complete combustion, determine (a) the air-fuel ratio on a mass basis and (b) the air-fuel ratio on a mole basis. (c) What-if Scenario: What would the air to fuel ratio be if propene (C_3H_6) were burned instead of acetylene?

SOLUTION:

(a) The equation for the following reaction is as follows:

$$\mathrm{C_2H_2} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \to b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

$$\mathrm{C}: 2 = b$$
$$\mathrm{H}: 2 = 2c$$
$$\mathrm{O}: 2a = 2b + c$$
$$\mathrm{N}: 3.76(2)a = 2d$$
$$\textit{Therefore};$$
$$a = 2.5;\ b = 2;\ c = 1;\ d = 18.8$$

$$\mathrm{C_2H_2} + 2.5(\mathrm{O_2} + 3.76\mathrm{N_2}) \to 2\mathrm{CO_2} + \mathrm{H_2O} + 18.8\mathrm{N_2}$$

$$\mathrm{AF} = \frac{\eta_{air}}{\eta_{fuel}};\ \eta_r = \frac{v_r \overline{M}_r}{\overline{M}_F}$$

$$\eta_{\mathrm{C_2H_2}} = 1\ \mathrm{kg}$$

$$\eta_{air} = \frac{(2.5)(4.76)(29)}{2(12) + 2(1)} = 13.27\ \mathrm{kg}$$

$$\mathrm{AF} = \frac{13.27}{1} = 13.27\ \frac{\mathrm{kg\ of\ air}}{\mathrm{kg\ of\ fuel}}$$

(b) The air-fuel ratio on mole basis is:

$$v_{\mathrm{C_2H_2}} = 1;\ v_{air} = 4.76(2.5)$$

$$\overline{\mathrm{AF}} = \frac{v_{air}}{v_{fuel}} = \frac{4.76(2.5)}{1} = 11.9\ \frac{\mathrm{kmol\ air}}{\mathrm{kmol\ fuel}}$$

TEST Verification and What-If Scenario: Use the n-IG non-premixed open-steady combustion TESTcalc to verify the results and perform the what-if study.

13-1-3 [OMY] For a theoretical (stoichiometric) hydrogen-air reaction at 200 kPa, find (a) the fuel-to-air mass ratio, (b) the mass of fuel per unit mass of reactants, (c) the partial pressure of water vapor in the products. Assume products temperature to be high enough for all H_2O to be in vapor form. (d) What-if Scenario: What is the minimum temperature of the products to ensure that water stays as vapor in the products?

SOLUTION:

The chemical balance equation:

$$\mathrm{H_2} + 0.5(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow \mathrm{H_2O} + 18.8\mathrm{N_2}$$

(a) The fuel to air mass ratio:

$$\frac{\eta_{fuel}}{\eta_{air}} = \frac{2}{(0.5)\,(4.76)\,(29)} = 0.029$$

(b) The mass of fuel per unit mass of reactants:

$$\frac{\eta_{fuel}}{\eta_{air}} = \frac{2}{(1.88)\,(28.01) + (18)} = 0.028$$

(c) The partial pressure of water vapor in the products:

$$p_{\mathrm{H_2O}} = \frac{1}{2.88}\,(200) = 69.4\ \text{kPa}$$

TEST Verification and What-If Scenario: Use the n-PG non-premixed open-steady combustion TESTcalc to verify the results and perform the what-if study.

13-1-4 [OMF] One kmol of octane (C_8H_{18}) is burned with air that contains 21 kmol of O_2. Assuming the products contain only 1) CO_2, 2) H_2O, 3) O_2 and 4) N_2, determine the (a) mole number of each gas in the products 1, 2, 3, and 4 and (b) the air-fuel ratio for this combustion process.

SOLUTION:

The theoretical reaction is expressed in terms of 1 kmol of fuel and unknown amounts (kmol) of air and products components.

$$C_8H_{18} + 21(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cO_2 + dN_2$$

Therefore four atom balance equations are:

$$\begin{aligned}
&\mathrm{C}: 8 = \mathrm{a} \\
&\mathrm{H}: 18 = 2\mathrm{b} \Rightarrow \mathrm{b} = 9 \\
&\mathrm{O}: 42 = 2\mathrm{a} + \mathrm{b} + 2\mathrm{c} \;\Rightarrow\; 42 = 16+9+2\mathrm{c} \Rightarrow \mathrm{c} = 8.5 \\
&\mathrm{N}: 21(3.76)2 = 2\mathrm{d} \;\Rightarrow \mathrm{d} = 78.96
\end{aligned}$$

Thus the theoretical equation becomes as follows

$$C_8H_{18} + 21(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 8.5O_2 + 78.96N_2$$

Therefore,

(a) Mole number of each gas in the products is as follows:

CO_2 : 8 kmol
H_2O : 9 kmol
O_2 : 8.5 kmol
N_2 : 78.96 kmol

(b) Thus mass based air-fuel ratio for this combustion process is as follows:

$$(\mathrm{AF})_{\mathrm{th}} = \frac{m_{\mathrm{Air}}}{m_F} = \frac{\nu_{\mathrm{Air}}\bar{M}_{\mathrm{Air}}}{\nu_F\bar{M}_F} = \frac{(21)(4.76)(29)}{(1)(114)} = 25.43\ \frac{\text{kg of air}}{\text{kg of fuel}}$$

TEST Verification: Use the non-premixed open-steady equilibrium combustion TESTcalc to verify the results.

13-1-5 [OMM] Ethane (C_2H_6) is burned with 30% excess air during a combustion process. Assuming complete combustion and a total pressure of 100 kPa, determine (a) the air-fuel ratio and (b) the dew point temperature of the products. (c) What-if Scenario: What would the air to fuel ratio be if methane were burned instead of ethane?

SOLUTION:

The chemical balance equation:

$$\mathrm{C_2H_6} + a\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

The four balance equations are:

$$\text{C:}\quad 1(2) = b(1);\quad \text{H:}\quad 6 = c(2);\quad \text{O:}\quad a(2) = 3(1) + 2(2);\quad \text{N:}\quad a(3.76)(2) = d(2)$$

Solving for the variables gives: $\mathrm{b} = 2;\quad c = 3;\quad a = 3.5;\quad d = 6.58$

The balanced equation for the theoretical reaction is therefore:

$$\mathrm{C_2H_6} + 3.5\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow 2\mathrm{CO_2} + 3\mathrm{H_2O} + 13.16\mathrm{N_2}$$

The theoretical air-fuel ratio on a molar basis is: $\dfrac{n_{air}}{n_f} = \dfrac{3.5(4.76)}{1} \Rightarrow \left(\overline{\mathrm{AF}}\right)_{th} = 16.66$

The theoretical air-fuel ratio on a mass basis is:

$$\frac{m_{air}}{m_f} = \frac{3.5(4.76)\bar{M}_{air}}{\bar{M}_{C_2H_6}} = \frac{3.5(4.76)(29\ \text{kg/kmol})}{(2\times 12 + 6\times 1)\ \text{kg/kmol}} \Rightarrow (\mathrm{AF})_{\mathrm{th}} = 16.1$$

To find the air-fuel ratio with 30% excess air, multiply $(\mathrm{AF})_{th}$ by 1.30:

(a)

$$\mathrm{AF} = (\mathrm{AF})_{\mathrm{th}}(1.30) = 16.1(1.30) = 20.9\ \frac{\text{kg air}}{\text{kg fuel}}$$

Adding in 30% excess air to the theoretical reaction gives:

$$\mathrm{C_2H_6} + 4.55\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow a\mathrm{CO_2} + b\mathrm{H_2O} + c\mathrm{N_2} + d\mathrm{O_2}$$

The four balance equations are:

$$\text{C:}\quad 2 = a(1);\quad \text{H:}\quad 6 = b(2);\quad \text{O:}\quad 4.55(2) = a(2) + b(1) + d(2);\quad \text{N:}\quad 4.55(3.76)(2) = c(2)$$

Solving for the variables gives: $a = 2; \quad b = 3; \quad c = 17.108; \quad d = 1.05$

Therefore, the balanced reaction with 30% excess air is given by:

$$C_2H_6 + 4.55(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 17.108N_2 + 1.05O_2$$

(b) The dew point temperature of the products is found from the partial pressure of H_2O in the products of the reaction:

$$\frac{\nu_{H_2O}}{\sum_p \nu_p} = \frac{p_v}{p}; \quad \Rightarrow \quad p_v = 100\frac{3}{(2+3+17.11+1.05)} = 12.95 \text{ kPa}$$

$$\Rightarrow \quad T_{dp} = T_{sat@12.95 \text{ kPa}} = 50.71°\text{C}$$

(c) How would the answer in part a) change if methane is burned instead of ethane?

Balancing the reaction for methane:

$$CH_4 + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

The four atom balance equations are given by:

$$\text{C:} \quad 1 = b(1); \quad \text{H:} \quad 4 = c(2); \quad \text{O:} \quad a(2) = 1(2) + 2(1); \quad \text{N:} \quad a(3.76)(2) = d(2)$$

Solving for the variables gives: $b = 1; \quad c = 2; \quad a = 2; \quad d = 7.52$

The balanced theoretical reaction is therefore:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

The theoretical air-fuel ratio on a mass basis is:

$$\frac{m_{air}}{m_f} = \frac{2(4.76)\bar{M}_{air}}{\bar{M}_{CH_4}} = \frac{2(4.76)(29)}{(12+4\times1)} \Rightarrow (\text{AF})_{th} = 17.26$$

To find the air-fuel ratio with 30% excess air, multiply $(\text{AF})_{th}$ by 1.30:

$$\text{AF} = (\text{AF})_{th}(1.30) = 17.26(1.30) = 22.44 \ \frac{\text{kg air}}{\text{kg fuel}}$$

TEST Verification and What-If Scenario: Use the n-PG non-premixed open-steady combustion TESTcalc to verify the results and perform the what-if study.

13-1-6 [OMJ] One kmol of methane (CH_4) is burned with an unknown amount of air. If the combustion is assumed complete and there are 2 kmol of free O_2 in the products, determine (a) the percent theoretical air used, (b) the excess air used (in percent), (c) the equivalence ratio.

SOLUTION:

(a) The theoretical reaction is expressed in terms of 1 kmol of fuel and unknown amounts (kmol) of air and products components.

$$\mathrm{CH_4} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2} + 2\mathrm{O_2}$$

$$\mathrm{O}: a = b + \frac{c}{2} + 2$$

$$\mathrm{C}:\ b = 1$$

$$\mathrm{N}: 3.76a = d$$

$$\mathrm{H}: c = 2$$

$$a = 1 + 1 + 2,\ a = 4$$

$$d = 15.04$$

Solving, the actual reaction can be written as:

$$\mathrm{CH_4} + 15.04(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O} + 15.04\mathrm{N_2} + 2\mathrm{O_2}$$

Balancing, the theoretical reaction can be written as:

$$\mathrm{CH_4} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

$$\mathrm{O}: a = b + \frac{c}{2}$$

$$\mathrm{C}:\ b = 1$$

$$\mathrm{N}: 3.76a = d$$

$$\mathrm{H}: c = 2$$

$$a = 1 + 1\ \ a = 2$$

$$d = 7.52$$

Solving, the theoretical reaction can be written as:

$$\mathrm{CH_4} + 2(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O} + 7.52\mathrm{N_2}$$

Comparing with actual and theoretical equation, the percent theoretical air can be seen as 15.04/7.52=200%.

(b) Excess air used is 100%.

(c) Equivalence ratio is:

$$\overline{\mathrm{AF}}_{\text{actual}} = \frac{n_{air}}{n_{fuel}} \Rightarrow \overline{\mathrm{AF}}_{\text{actual}} = \frac{116}{16} \Rightarrow \overline{\mathrm{AF}}_{\text{actual}} = 7.25$$

$$\overline{\mathrm{AF}}_{theoretical} = \frac{n_{air}}{n_{fuel}} \Rightarrow \overline{\mathrm{AF}}_{theoretical} = \frac{58}{16} \Rightarrow \overline{\mathrm{AF}}_{\text{actual}} = 3.625$$

$$\text{theoritical air}(\lambda) = \frac{\overline{\mathrm{AF}}_{\text{actual}}}{\overline{\mathrm{AF}}_{\text{th}}} \Rightarrow \lambda = 2$$

$$\text{equivalent ratio } (\varphi) = \frac{1}{\lambda} \Rightarrow \varphi = 0.5$$

13-1-7 [OJR] Determine the air-fuel ratio for hydrogen (H_2) burning with (a) 50% excess air and (b) 50% deficient air.

SOLUTION:

$$H_2 + a\left(O_2 + 3.76N_2\right) \rightarrow bH_2O + cN_2$$
$$\mathrm{H}: 2 = 2b$$
$$b = 2$$
$$\mathrm{O}: 2a = b$$
$$a = \frac{1}{2}$$
$$\mathrm{N}: \frac{3.76}{2} = c$$
$$c = 1.88$$

Theoretical combustion gives the following balanced mole fraction equation.

$$H_2 + \frac{1}{2}\left(O_2 + 3.76N_2\right) \rightarrow H_2O + 1.88N_2$$
$$\left(\mathrm{AF}\right)_{th} = 0.5(4.76) = 2.38$$

(a) 50% Excess Air:

50% Excess Air =150% Theoretical Air

$$150\% = \frac{(\mathrm{AF})_{actual}}{\left(\mathrm{AF}\right)_{theorectical}} = \frac{(\mathrm{AF})_{actual}}{2.83}$$

$$(\mathrm{AF})_{actual} = 3.57$$

(b) 50% Deficient Air:

50% Deficient Air =50% Theoretical Air

$$50\% = \frac{(\mathrm{AF})_{actual}}{\left(\mathrm{AF}\right)_{theorectical}} = \frac{(\mathrm{AF})_{actual}}{2.38}$$

$$(\mathrm{AF})_{actual} = 1.19$$

TEST Verification: Use the n-PG model non-premixed open-steady combustion TESTcalc to verify the results.

13-1-8 [OJB] Determine the air-fuel ratio on a mass basis for the complete combustion of octane, C_8H_{18}, with (a) the theoretical amount of air. (b) What-if Scenario: What would the theoretical amount of air be if complete combustion occurred in 120% theoretical air (20% excess air)?

SOLUTION:

(a) The theoretical amount of air:

The chemical balance equation:

$$C_8H_{18} + a\left(O_2 + 3.76N_2\right) \rightarrow bCO_2 + cH_2O + dN_2$$

$$\begin{aligned}
&C: 8 = b \Rightarrow b = 8 \\
&H: 18 = 2c \Rightarrow c = 9 \\
&O: 2a = 2b + c \Rightarrow a = 12.5 \\
&N: (2)(3.76)(a) = 2d \Rightarrow d = 47
\end{aligned}$$

Therefore;

$$C_8H_{18} + 12.5\left(O_2 + 3.76N_2\right) = 8CO_2 + 9H_2O + 47N_2$$

$$(AF)_{th} = \left(\overline{AF}\right)_{th}\left(\frac{\overline{M}_{air}}{\overline{M}_{fuel}}\right) = (12.5)(4.76)\frac{28.97}{114.231} = (AF)_{th} = 15.09$$

(b) With 120% theoretical air:

$$AF = (1.2)(AF)_{th} = (1.2)(15.1) = 18.11$$

TEST Verification: Use the n-PG model non-premixed open-steady combustion TESTcalc to verify the results.

13-1-9 [OJO] Octane, C_8H_{18}, is burned with 150% theoretical air, determine the (a) molar analysis of the products of combustion and (b) the dew point of the products if the pressure is 0.1 MPa.

SOLUTION:

(a) Molar analysis of the products of combustion:

Theoretical reaction:

$$\mathrm{C_8H_{18}} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

$$\begin{aligned}&\mathrm{H}: c = 9\\ &\mathrm{C}: b = 8\\ &\mathrm{N_2}: d = 3.76a\\ &\mathrm{O_2}: 2a = 16 + 9 \rightarrow a = \frac{25}{2} = 12.5 \rightarrow d = (3.76)(12.5) = 47\end{aligned}$$

Balance reaction is:

$$\mathrm{C_8H_{18}} + 12.5(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 8\mathrm{CO_2} + 9\mathrm{H_2O} + 47\mathrm{N_2}$$

With 150% air:

$$\mathrm{C_8H_{18}} + 18.75(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 8\mathrm{CO_2} + 9\mathrm{H_2O} + 70.5\mathrm{N_2} + 6.25\mathrm{O_2}$$

$$\frac{n_{\mathrm{CO_2}}}{n} = \frac{8}{8 + 9 + 70.5 + 6.25} = 8.53\%$$

$$\frac{n_{\mathrm{H_2O}}}{n} = \frac{9}{8 + 9 + 70.5 + 6.25} = 9.6\%$$

$$\frac{n_{\mathrm{N_2}}}{n} = \frac{70.5}{8 + 9 + 70.5 + 6.25} = 75.2\%$$

$$\frac{n_{\mathrm{O_2}}}{n} = \frac{6.25}{8 + 9 + 70.5 + 6.25} = 6.67\%$$

(b) Dew point:

$$p_v = \frac{9}{8 + 9 + 70.5 + 6.25}0.1 = 9.6 \text{ kPa} \rightarrow T_{sat@p_v} \approx 45^\circ\mathrm{C}$$

TEST Verification: Use the n-PG Model non-premixed open-steady combustion TESTcalc to verify the results.

13-1-10 [OMW] Octane, C_8H_{18}, is burned with theoretical amount of air at 500 kPa. Determine (a) the air fuel ratio on a mole basis and (b) the air fuel ratio on a mass basis. (c) If the products are cooled at a constant pressure of 500 kPa, at what temperature will dew start to form? (d) Suppose the products are cooled below the dew point temperature so that all the water from the products are removed (neglect any vapor which may still be present at very low amount). What would be the volume fraction of CO_2 in the dry products? If you have a smog test report of your gasoline burning car at hand, compare the CO_2 amount (in percent).

SOLUTION:

The chemical balance equation:

$$\mathrm{C_8H_{18}} + a(\mathrm{O_2} + 3.76\ \mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

To determine our coefficients, we can balance the numerical values:

$$b = 8$$
$$2c = 18 \Rightarrow c = 9$$
$$2a = 2b + c \Rightarrow a = 12.5$$
$$3.76a = d \Rightarrow d = 47$$

Since this is a stoichiometric reaction, we can directly write our final chemical equation:

$$\mathrm{C_8H_{18}} + 12.5(\mathrm{O_2} + 3.76\ \mathrm{N_2}) \rightarrow 8\mathrm{CO_2} + 9\mathrm{H_2O} + 47\mathrm{N_2}$$

(a) The air fuel ratio on a mole basis:

$$\mathrm{AF} = \frac{n_{air}}{n_{fuel}} \Rightarrow \mathrm{AF} = \frac{12.5\ (4.76)}{1} = 59.5$$

(b) The air fuel ratio on a mass basis:

$$\mathrm{AF} = \frac{m_{air}}{m_{fuel}} \Rightarrow \mathrm{AF} = \frac{12.5\ (4.76)\ (29)}{114.23} = 15.105$$

(c) Dew point:

$$y_{\mathrm{H_2O}} = \frac{\eta_{\mathrm{H_2O}}}{\eta_{\mathrm{mixture}}} = \frac{P_v}{P_{\mathrm{total}}} = \frac{9}{8 + 9 + 47} = 0.1406$$

$$P_v = 0.1406\ (500) = 70.3125\ \mathrm{kPa}$$

From TEST with the found pressure:

$T_{DP} = T_{sat@P_v} = 89.62\ °C$

(d) If all the water would be removed, we would now have the following species present in our products:

$8CO_2 + 47N_2$

The volume fraction can be determined from the mole fraction:

$$y_{CO_2} = \frac{\eta_{CO_2}}{\eta_{mixture}} = \frac{v_{CO_2}}{v_{total}} = \frac{8}{8+47} = 0.145 = 14.5\%$$

TEST Verification: Use the n-PG Model non-premixed open-steady combustion TESTcalc to verify the results.

13-1-11 [OJH] Methane, CH_4, is burned with dry air. The molar analysis of the products on a dry basis is CO_2: 8%; CO: 1%; O_2: 3%; and N_2: 77.11%. Determine (a) the air fuel ratio on both a molar and a mass basis, and (b) the percent theoretical air.

SOLUTION:

Balance the reaction and then determine AF and $\overline{\text{AF}}$ the write the theoretical reaction and compare $\left(\overline{\text{AF}}\right)_{th}$ with $\overline{\text{AF}}$ to get % theoretical air.

$$\text{CH}_4 + c(\text{O}_2 + 3.76\text{N}_2) \rightarrow a(8\text{CO}_2 + \text{CO} + 3\text{O}_2 + 77.11\text{N}_2) + b\text{H}_2O$$

$$a = \frac{1}{9};\ b = 2;\ c = \frac{7711}{3384} \approx 2.28$$

$$\text{CH}_4 + 2.28\,(\text{O}_2 + 3.76\text{N}_2) \rightarrow \frac{8}{9}\,(8\,\text{CO}_2 + \frac{1}{9}\text{CO} + \frac{1}{3}\,\text{O}_2 + 8.57\,\text{N}_2) + 2\,\text{H}_2O$$

(a) $\overline{\text{AF}} = 4.76c \approx$ 10.85

$$\text{AF} = \frac{n_{air}\overline{M}_{air}}{n_{\text{CH}_4}\overline{M}_{\text{CH}_4}} = \overline{\text{AF}}\frac{\overline{M}_{air}}{\overline{M}_{\text{CH}_4}} \approx 4.76c\frac{29}{12+4} \approx 19.66$$

(b) Theoretical reaction:

$$\text{CH}_4 + d\ (\text{O}_2 + 3.76\text{N}_2) \rightarrow e\ \text{CO}_2 + f\ \text{N}_2 + \text{g}\ \text{H}_2O$$
$$\text{CH}_4 + 2\ (\text{O}_2 + 3.76\text{N}_2) \rightarrow \text{CO}_2 + 7.52\ \text{N}_2 + 2\ \text{H}_2O$$

$$\left(\overline{\text{AF}}\right)_{\text{th}} = 4.76d$$

$$\text{Percent theoretical air} = \frac{\overline{\text{AF}}}{\left(\overline{\text{AF}}\right)_{\text{th}}} = \frac{4.76c}{4.76d} = \frac{c}{d} \approx 113.9\%$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-12 [OJN] A natural gas has the following molar analysis. CH_4: 81.62%; C_2H_6: 4.41%; C_3H_8: 1.85%; C_4H_{10}: 1.62%; N_2: 10.50%. The gas is burned with dry air, giving products having a molar analysis on a dry basis: CO_2: 8.8%; CO: 0.2%; O_2: 6%; N_2: 85 %. Determine (a) the air fuel ratio on a molar basis.

SOLUTION:

Balance the theoretical and actual reaction.

$$0.8162\,CH_4 + 0.0441\,C_2H_6 + 0.0185\,C_3H_8 + 0.0162\,C_4H_{10} + 0.105\,N_2 + a(O_2 + 3.76N_2) \rightarrow$$

$$b(0.088\,CO_2 + 0.002\,CO + 0.06\,O_2 + 0.85N_2) + cH_2O$$

Conservation of mass for carbon,

$$b(0.088 + 0.002) = 0.009 + 2(0.0441) + 3(0.0185) + 4(0.0162)$$

$$C:\ b = 11.4$$

Conservation of mass for hydrogen,

$$2c = 4(0.8162) + 6(0.0441) + 8(0.0185) + 10(0.0162)$$

$$H:\ c = 1.92$$

Conservation of mass for oxygen,

$$11.385[2(0.088) + 0.002 + 2(0.06)] + 1.92 = 2a$$

$$O:\ a = 2.66$$

The balanced chemical equation is then,

$$0.8162CH_4 + 0.0441C_2H_6 + 0.0185C_3H_8 + 0.0162C_4H_{10} + 0.105N_2 + 2.66(O_2 + 3.76N_2)$$

$$\rightarrow 11.4(0.088\,CO_2 + 0.002\,CO + 0.06\,O_2 + 0.85N_2) + 1.92H_2O$$

The air-fuel ratio on a molar basis,

$$(AF) = \frac{n_{air}}{n_{fuel}} = \frac{2.66(4.76)}{1} = 12.66\,\frac{\text{mole of air}}{\text{mole of fuel}}$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-13 [OJE] One kmol of ethane (C_2H_6) is burned with unknown amount of air during a combustion process. An analysis of the combustion products reveals that the combustion is complete, and there are 3 kmol of free O_2 in the products. Determine (a) the air fuel ratio and (b) the percentage of theoretical air (λ) used during the process.

SOLUTION:

The theoretical reaction is expressed in terms of 1 kmol of fuel and unknown amounts (kmol) of air and products components.

$$\mathrm{C_2H_6} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2} + 3\mathrm{O_2}$$

$$\mathrm{O}: a = b + \frac{c}{2} + 3$$

$$\mathrm{C}:\ b = 2$$

$$\mathrm{N}: 3.76a = d$$

$$\mathrm{H}: c = 3$$

$$a = 2 + 1.5 + 3,\ a = 6.5$$

$$d = 24.44$$

Solving, the actual reaction can be written as

$$\mathrm{C_2H_6} + 6.5(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 2\mathrm{CO_2} + 3\mathrm{H_2O} + 24.44\mathrm{N_2} + 3\mathrm{O_2}$$

The mass-based air-fuel ratio now can be obtained from the equation above

$$(\mathrm{AF})_{th} = \frac{m_{Air}}{m_F} = \frac{\nu_{Air}\bar{M}_{Air}}{\nu_F\bar{M}_F} = \frac{6.5(4.79)29}{(1)30} = 29.91\frac{\text{kg of air}}{\text{kg of fuel}}$$

Balancing, the theoretical reaction can be written as:

$$\mathrm{C_2H_6} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

$$\mathrm{O}: a = b + \frac{c}{2}$$

$$\mathrm{C}:\ b = 2$$

$$\mathrm{N}: 3.76a = d$$

$$\mathrm{H}: c = 3$$

$$a = 2 + 1.5,\ a = 3.5$$

$$d = 16.66$$

Solving, the theoretical reaction can be written as:

$$\mathrm{C_2H_6} + 3.5(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 2\mathrm{CO_2} + 3\mathrm{H_2O} + 16.66\mathrm{N_2}$$

Comparing with actual and theoretical equation, the percent theoretical air can be seen as 6.5/3.5=186%.

TEST Verification: Use the non-premixed open-steady combustion TESTcalc to verify the results.

13-1-14 [OJI] Coal from Kentucky has the following analysis on a dry basis, percent by mass. S: 0.8%; H_2: 5.4%; C: 80.1%; O_2: 9.5%; N_2: 1.2%; Ash: 3%. This coal is burned with 40% excess air. Determine the (a) air-fuel ratio on a mass basis. (b) What-if Scenario: What would the air to fuel ratio be if the coal were burned with theoretical amount of air?

SOLUTION:

100 kg of the fuel has the following molar composition

$$\left(\frac{0.8}{\bar{M}_S}\right)\mathrm{S}+\left(\frac{5.4}{\bar{M}_{H_2}}\right)\mathrm{H_2}+\left(\frac{80.1}{\bar{M}_C}\right)\mathrm{C}+\left(\frac{9.5}{\bar{M}_{O_2}}\right)\mathrm{O_2}+\left(\frac{1.2}{\bar{M}_{N_2}}\right)\mathrm{N_2}$$

$$=\left(\frac{0.8}{33.33}\right)\mathrm{S}+\left(\frac{5.4}{2}\right)\mathrm{H_2}+\left(\frac{80.1}{12}\right)\mathrm{C}+\left(\frac{9.5}{32}\right)\mathrm{O_2}+\left(\frac{1.2}{28}\right)\mathrm{N_2}$$

$$=0.024\mathrm{S}+2.7\mathrm{H_2}+6.675\mathrm{C}+0.2968\mathrm{O_2}+0.0428\mathrm{N_2}$$

The reaction can be written as:

$$0.024\mathrm{S}+2.7\mathrm{H_2}+6.675\mathrm{C}+0.2968\mathrm{O_2}+0.0428\mathrm{N_2}+(\mathrm{O}+\ 3.76\mathrm{N_2})\rightarrow \mathrm{CO_2}+\mathrm{SO_2}+\mathrm{H_2O}+\mathrm{N_2}$$

The reaction is expressed in 100kg of fuel and unknown coefficients of all other components

Balancing the reaction:

$$0.024\mathrm{S}+2.7\mathrm{H_2}+6.675\mathrm{C}+0.2968\mathrm{O_2}+0.0428\mathrm{N_2}+a\left(\mathrm{O_2}+3.76\mathrm{N_2}\right)\rightarrow \mathrm{CO_2}+d\mathrm{SO_2}+c\mathrm{H_2O}+e\mathrm{N_2}$$

The six atom balance equations are:

$\mathrm{C}: b=6.675$

$\mathrm{H}: c=2.7$

$S: \mathrm{d}=0.024$

$\mathrm{O}: 2b+c+2d=(0.2962x2)+2a\Rightarrow a=7.7522$

$\mathrm{N}: 2e=(0.0428\ x\ 2)+(a\ x\ 3.76\ x\ 2)\Rightarrow \mathrm{e}=29.191072$

The balanced reaction:

$$(0.024\mathrm{S}+2.7\mathrm{H_2}+6.675\mathrm{C}+0.2968\mathrm{O_2}+0.0428\mathrm{N_2})+7.752(\mathrm{O_2}+3.76\mathrm{N_2})\rightarrow$$
$$6.675\mathrm{CO_2}+0.024\mathrm{SO_2}+2.7\mathrm{H_2O}+29.191072\mathrm{N_2}$$

Air-Fuel ratio on mass basis (40% excess air is used for burning coal)

The mass of air can be calculated as = 7.7522 x 1.4 x 29 x 4.76 = 1498.15 per 100kg of coal.
Thus the Air-Fuel ratio on mass basis is 14.98 kg/kg fuel

TEST Verification: It is not possible to solve this question by TEST.

13-1-15 [OJL] Coal with a mass analysis of 79% carbon, 5% sulfur and 17% noncombustible ash burns completely with 110% of theoretical air. Determine (a) the amount of SO_2 produced, in kg per kg of coal.

SOLUTION:

$$\left(\frac{79}{\bar{M}_C}\right)\mathrm{C}+\left(\frac{5}{\bar{M}_S}\right)\mathrm{S}=\left(\frac{79}{12.0107}\right)\mathrm{C}+\left(\frac{5}{32.065}\right)\mathrm{S}=(6.57)\mathrm{C}+(0.15)\mathrm{S}$$

The theoretical reaction can be written as:

$$6.57\mathrm{C}+0.15\mathrm{S}+a(\mathrm{O_2}+3.76\mathrm{N_2})\rightarrow b\mathrm{CO_2}+c\mathrm{SO_2}+d\mathrm{N_2}$$

Balancing the reaction:

$$6.57\mathrm{C}+0.15\mathrm{S}+6.72(\mathrm{O_2}+3.76\mathrm{N_2})\rightarrow 6.57\mathrm{CO_2}+0.15\mathrm{SO_2}+25.26\mathrm{N_2}$$

The reaction with 110% air:

$$6.57\mathrm{C}+0.15\mathrm{S}+1.1a(\mathrm{O_2}+3.76\mathrm{N_2})\rightarrow b\mathrm{CO_2}+c\mathrm{SO_2}+d\mathrm{N_2}+e\mathrm{O_2}$$

$$6.57\mathrm{C}+0.15\mathrm{S}+7.392(\mathrm{O_2}+3.76\mathrm{N_2})\rightarrow 6.57\mathrm{CO_2}+0.15\mathrm{SO_2}+27.8\mathrm{N_2}+7.392\mathrm{O_2}$$

Mass of SO_2 is $(0.15)(64.066)=9.61\text{ kg}$
Mass of coal is $(6.57)(12.0107)+(0.15)(32.065)=80.116\text{ kg}$

$$\frac{\text{mass of SO}_2}{\text{mass of coal}}=\frac{9.61}{80.116}=0.12$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-16 [OJG] Diesel (dodecane) is burned with air at an air-fuel ratio of 30 kg of air/kg fuel. Determine the percent of theoretical air (λ) used.

SOLUTION:

Theoretical Reaction:

$$C_{12}H_{26} + a(O_2 + 3.76N_2) \rightarrow dCO_2 + bH_2O + cN_2$$

$$C: d = 12$$
$$H: 2b = 26 \Rightarrow b = 13$$
$$O: 2a = b + 2d \Rightarrow a = 18.5$$
$$N: 2(3.76)a = 2c \Rightarrow c = 139.2$$

$$C_8H_{18} + 18.5(O_2 + 3.76N_2) \rightarrow 13CO_2 + 139.2H_2O + 12N_2$$

$$\eta_{air} = \frac{(18.5)(4.76)(29)}{170} = 15$$

$$AF_{th} = \eta_{air} = 15 \ \frac{\text{kg air}}{\text{kg fuel}}$$

$$AF = 30 \ \frac{\text{kg air}}{\text{kg fuel}}$$

$$\%\text{Theoretical Air} = \frac{AF}{AF_{th}} = \frac{30}{15} = 200\%$$

TEST Verification: Use the n-IG non-premixed open-steady combustion TESTcalc to verify the results.

13-1-17 [OJZ] Octane (C_8H_{18} in gaseous form) is burned with dry air. The volumetric analysis of the products on a dry basis is 8.86% CO_2, 0.662% CO, 7.51% O_2 and 82.978% N_2. Determine (a) the air-fuel ratio and (b) the percentage of stoichiometric air used. If the initial pressure and temperature of the fuel air mixture are 100 kPa, 25^{o}C, determine (c) the final pressure (p_2) if the combustion chamber is an insulated closed tank and the amount of fuel is 1 kmol.

SOLUTION:

$$a\mathrm{C_8H_{18}} + b\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow 8.86\mathrm{CO_2} + 0.662\mathrm{CO} + 7.51\mathrm{O_2} + 82.978\mathrm{N_2} + c\mathrm{H_2O}$$

(a) air-fuel ratio

Atom balance equations:

$$\mathrm{C}: 8a = 9.522 \Rightarrow a = 1.19025$$
$$\mathrm{H}: 18a = 2c \;\; \Rightarrow \;\; \mathrm{b} = 22.0571$$
$$\mathrm{O}: 2b = 33.402 + c \Rightarrow c = 10.7122$$
$$\mathrm{N}: 7.52b = 165.956$$

$$\left(1.19025\right)\mathrm{C_8H_{18}} + \left(22.0571\right)\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow 8.86\mathrm{CO_2} + 0.662\mathrm{CO} + 7.51\mathrm{O_2} + 82.978\mathrm{N_2} + 10.7122\mathrm{H_2O}$$

Normalizing the reaction:

$$\mathrm{C_8H_{18}} + \left(18.5\right)\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow 7.44\mathrm{CO_2} + 0.556\mathrm{CO} + 6.31\mathrm{O_2} + 69.7\mathrm{N_2} + 9.00\mathrm{H_2O}$$
$$\overline{\mathrm{AF}} = (18.5)(4.76) = 88.1$$

(b) % of stoichiometric air used:

Theoretical reaction between octane and dry air:
$$\mathrm{C_8H_{18}} + 8.5\left(\mathrm{O_2} + 3.76\mathrm{N_2}\right) \rightarrow 8\mathrm{CO_2} + 9\mathrm{H_2O} + 31.96\mathrm{N_2}$$
$$\% = \left(\frac{18.5}{8.5}\right)\left(100\right) = 218\%$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-18 [OJK] Analysis of the dry exhaust products from a burner which uses natural gas and air reads 5% O_2 and 9% CO_2. Find the excess air used in this burner.

SOLUTION:

The theoretical reaction is;

$$CH_4 + 2\left(O_2 + 3.76N_2\right) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

The actual reaction is;

$$CH_4 + a\left(O_2 + 3.76N_2\right) \rightarrow 0.09CO_2 + bH_2O + cN_2 + 0.05O_2$$

Balancing the reaction;

$$CH_4 + 1.595\left(O_2 + 3.76N_2\right) \rightarrow 0.09CO_2 + 0.91CO + 2H_2O + 6N_2 + 0.05O_2$$

The excess air used is:

$$\frac{n_{actual}}{n_{theoretical}} x100 = \frac{2}{1.595} x100 = 125.4\%$$

$\Rightarrow$ %25.4

TEST Verification: Use the n-IG non-premixed open-steady combustion TESTcalc to verify the results.

13-1-19 [OJP] One kmol of ethane (C_2H_6) is burned with an unknown amount of air. If the combustion is assumed complete and there are 2 kmol of free O_2 in the products, determine (a) the percent theoretical air (λ) used, (b) the excess air used (in percent), and (c) the equivalence ratio (φ).

SOLUTION:

(a) The theoretical reaction is expressed in terms of 1 kmol of fuel and unknown amounts (kmol) of air and products components.

$$C_2H_6 + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2 + 2O_2$$

$$O: a = b + \frac{c}{2} + 2$$

$$C: \ b = 2$$

$$N: 3.76a = d$$

$$H: c = 3$$

$$a = 2 + 1.5 + 2, \ a = 5.5$$

$$d = 20.68$$

Solving, the actual reaction can be written as:

$$C_2H_6 + 5.5(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 20.68N_2 + 2O_2$$

Balancing, the theoretical reaction can be written as:

$$C_2H_6 + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

$$O: a = b + \frac{c}{2}$$

$$C: \ b = 2$$

$$N: 3.76a = d$$

$$H: c = 3$$

$$a = 2 + 1.5, \ a = 3.5$$

$$d = 16.66$$

Solving, the theoretical reaction can be written as:

$$C_2H_6 + 3.5(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 16.66N_2$$

Comparing with actual and theoretical equation, the percent theoretical air can be seen as 5.5/3.5=157.14%.

(d) Excess air used is 57.14%.

(e) Equivalence ratio is:

$$\overline{\mathrm{AF}}_{\mathrm{actual}} = \frac{n_{air}}{n_{fuel}} \Rightarrow \overline{\mathrm{AF}}_{\mathrm{actual}} = \frac{759.22}{30} \Rightarrow \overline{\mathrm{AF}}_{\mathrm{actual}} = 25.307$$

$$\overline{\mathrm{AF}}_{\mathrm{theoretical}} = \frac{n_{air}}{n_{fuel}} \Rightarrow \overline{\mathrm{AF}}_{\mathrm{theoretical}} = \frac{483.14}{30} \Rightarrow \overline{\mathrm{AF}}_{\mathrm{actual}} = 16.104$$

$$\text{theoritical air}(\lambda) = \frac{\overline{\mathrm{AF}}_{\mathrm{actual}}}{\overline{\mathrm{AF}}_{\mathrm{th}}} \Rightarrow \lambda = 1.57$$

$$\text{equivalent ratio } (\varphi) = \frac{1}{\lambda} \Rightarrow \varphi = 0.63$$

TEST Verification: Use the n-IG non-premixed open-steady combustion TESTcalc to verify the results.

13-1-20 [OJU] Producer gas from bituminous coal has the following analysis on molar basis. CH_4: 3%; H: 14%; N_2: 50.9%; O_2: 0.6%; CO: 27%; CO_2: 4.5%. It is burned with 30% excess air. Determine (a) the air-fuel ratio on mass basis.

SOLUTION:

The chemical balance equation:

$$\left(\mathrm{CH_4}+\mathrm{CO}+\mathrm{O_2}+\mathrm{N_2}+\mathrm{H}+\mathrm{CO_2}\right)+1.3(\mathrm{a})\left(\mathrm{O_2}+3.76\mathrm{N_2}\right)\rightarrow b\mathrm{CO_2}+c\mathrm{H_2O}+d\mathrm{N_2}$$

Balancing, the theoretical reaction can be written as:

$$\begin{aligned}&\mathrm{C}: 1+1+1 \Rightarrow b=3\\&\mathrm{H}: 4+1=2c \ \Rightarrow\ \mathrm{c}=2.5\\&\mathrm{O}: 3(2)+2.5=2+2+1.3(2)a \Rightarrow a=1.346\\&\mathrm{N}: (1.3)(1.346)(3.76)a=d \Rightarrow d=6.58\end{aligned}$$

Solving, the reaction can be written as:

$$\left(\mathrm{CH_4}+\mathrm{CO}+\mathrm{O_2}+\mathrm{N_2}+\mathrm{H}+\mathrm{CO_2}\right)+1.75\left(\mathrm{O_2}+3.76\mathrm{N_2}\right)\rightarrow 3\mathrm{CO_2}+2.5\mathrm{H_2O}+6.58\mathrm{N_2}$$

(a) The air-fuel ratio on molar basis:

$$(\mathrm{AF})_{\mathrm{th}}=\frac{m_{\mathrm{air}}}{m_{fuel}}=\frac{n_{\mathrm{air}}\bar{M}_{\mathrm{air}}}{n_{fuel}\bar{M}_{fuel}}=\frac{(1.75)(4.76)(29)}{(16.04)+(1)+(28)+(32)+(28)+(44)}=1.63\ \frac{\text{kg of air}}{\text{kg of fuel}}$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-21 [OJX] A fuel mixture having a molar analysis of 70% CH_4, 20% CO, 5% O_2 and 5% N_2 burns completely with 130% of theoretical air. Determine (a) the air-fuel ratio on a mass and (b) mole basis.

SOLUTION:

The chemical balance equation:

$$\left(0.7CH_4 + 0.2CO + 0.05O_2 + 0.05N_2\right) + (a)\left(O_2 + 3.76N_2\right) \rightarrow bCO_2 + cH_2O + dN_2$$

$$\begin{aligned}
&C: 0.7 + 0.2 = b = 0.9 \\
&H: 4(0.7) = 2c \;\Rightarrow\; c = 1.4 \\
&O: 0.2 + 2(0.05) + 2a = 2b \Rightarrow a = 1.45 \\
&N: 2(0.05) + 2(3.76)a = 2d \Rightarrow d = 5.502
\end{aligned}$$

Balancing the reaction;

$$\left(0.7CH_4 + 0.2CO + 0.05O_2 + 0.05N_2\right) + 1.45\left(O_2 + 3.76N_2\right) \rightarrow 0.9CO_2 + 1.4H_2O + 5.502N_2$$

Therefore:

$$AF = \frac{(\%\text{ theoretical air})\left(\text{kmol}_{\text{air}}\right)\left(\overline{M}_{\text{air}}\right)}{\sum\left(\%\text{ composition}_k\right)\left(\overline{M}_{\text{fuel}_k}\right)}$$

$$AF = \frac{(1.3)(1.45)(4.76)(28.97)}{(0.7)(16.043) + (0.2)(28.011) + (0.05)(32) + (0.05)(28.013)} = 13.11\,\frac{\text{kg of air}}{\text{kg of fuel}}$$

And:

$$\overline{AF} = (1.3)\left(\overline{AF}\right)_{\text{th}} = (1.3)(1.45)(4.76) = 8.97\,\frac{\text{kmol of air}}{\text{kmol of fuel}}$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-22 [OJC] Octane (C_8H_{18}) is burned with dry air. The volumetric analysis of the products on a dry basis is 10.02% CO_2, 0.88% CO, 5.62% O_2 and 83.48% N_2. Determine (a) the air-fuel ratio and (b) the percentage of theoretical air (λ) used.

SOLUTION:

(a) The air-fuel ratio:

The chemical balance equation:

$$\mathrm{C_8H_{18}} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b(10.02\mathrm{CO_2} + 0.88\mathrm{CO} + 5.62\mathrm{O_2} + 83.48\mathrm{N_2}) + c\mathrm{H_2O}$$

$$\begin{aligned}
&\mathrm{C}: 8 = 10.02b + 0.88b \\
&\mathrm{H}: 18 = 2c \\
&\mathrm{O}: 2a = 2b(10.02) + b(0.88) + 2b(5.62) + c \\
&\mathrm{N}: 2a(3.76) = 2b(83.48)
\end{aligned}$$

Therefore;

$a = 16.3;\ b = 0.7339;\ c = 9$

$$\mathrm{AF} = \frac{\eta_{\mathrm{Air}}}{\eta_{\mathrm{Fuel}}}; \eta_r = \frac{v_r \overline{M}_r}{\overline{M}_F}$$

$$\eta_{\mathrm{C_8H_{18}}} = 1\ \mathrm{kg}$$

$$\eta_{\mathrm{Air}} = \frac{16.3(4.76)(29)}{8(12) + 18(1)} = 19.73\ \mathrm{kg}$$

$$\mathrm{AF} = \frac{19.73}{1} = 19.73 \frac{\text{kg of air}}{\text{kg of fuel}}$$

b) The percentage of air used:

$$\text{Percent Theoretical Air} = \frac{\text{AF}}{(\text{AF})_{\text{th}}}$$

$$C_8H_{18} + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

$$\begin{aligned}
&\text{C}: 8 = b \\
&\text{H}: 18 = 2c \\
&\text{O}: 2a = 2b + c \\
&\text{N}: a(2)(3.76) = 2d \\
&a = 12.5; b = 8; c = 9; d = 63.92
\end{aligned}$$

$$(\text{AF})_{\text{th}} = \frac{12.5(4.76)(29)}{8(12) + 18(1)} = 15.14 \frac{\text{kg of air}}{\text{kg of fuel}}$$

$$\text{Percent Theoretical Air} = \frac{\text{AF}}{(\text{AF})_{\text{th}}} = \frac{19.73}{15.14} = 130.3\%$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-23 [OJT] A fuel mixture having a molar analysis of 65% CH_4, 25% C_2H_6, 10% N_2 is supplied to a furnace where it burns completely with 120% of theoretical air. Determine (a) the air-fuel ratio on a mass basis. (b) What-if Scenario: What would the air to fuel ratio be if the fuel had 25% of C_2H_4 instead of C_2H_6?

SOLUTION:

The theoretical balance equation:

$$0.65\mathrm{CH_4} + 0.25\mathrm{C_2H_6} + 0.1\mathrm{N_2} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

(a) $0.65\mathrm{CH_4} + 0.25\mathrm{C_2H_6} + 0.1\mathrm{N_2} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$

$$\mathrm{C}: 0.65 + 0.25(2) = b \rightarrow b = 1.15$$
$$\mathrm{H}: 0.65(4) + 0.25(6) = 2c \rightarrow c = 2.05$$
$$\mathrm{O}: (2)a = 1.15(2) + 2.05 \rightarrow a = 2.175$$
$$\mathrm{N}: 0.1(2) + (2.175)(3.76)(2) = 2d \rightarrow d = 8.278$$

Balanced reaction:

$$0.65\mathrm{CH_4} + 0.25\mathrm{C_2H_6} + 0.1\mathrm{N_2} + 2.61(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 1.15\mathrm{CO_2} + 2.05\mathrm{H_2O} + 9.92\mathrm{N_2} + 0.435\mathrm{O_2}$$

$$\mathrm{CH_4} + 0.38\mathrm{C_2H_6} + 0.15\mathrm{N_2} + 4.01(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 1.77\mathrm{CO_2} + 3.15\mathrm{H_2O} + 15.26\mathrm{N_2} + 0.67\mathrm{O_2}$$

$$\mathrm{AF} = \frac{m_{air}}{m_{fuel}} = \frac{4.01\,(4.76)\,(29)}{(16) + 0.38\,(30) + 0.15\,(28)} = 17.52\,\frac{\text{kg of air}}{\text{kg of fuel}}$$

(b) Theoretical reaction:

$$0.65\mathrm{CH_4} + 0.25\mathrm{C_2H_4} + 0.1\mathrm{N_2} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

$$\mathrm{C}: 0.65 + 0.25(2) = b \Rightarrow b = 1.15$$
$$\mathrm{H}: 0.65(4) + 0.25(4) = 2c \Rightarrow c = 1.8$$
$$\mathrm{O}: (2)a = 1.15(2) + 1.8 \Rightarrow a = 2.05$$
$$\mathrm{N}: 0.1(2) + (1.7)(3.76)(2) = 2d \Rightarrow d = 7.808$$

Balanced reaction:

$$0.65\mathrm{CH_4} + 0.25\mathrm{C_2H_6} + 0.1\mathrm{N_2} + 2.46(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 1.15\mathrm{CO_2} + 1.8\mathrm{H_2O} + 7.808\mathrm{N_2}$$

Actual reaction:

$$0.65CH_4 + 0.25C_2H_6 + 0.1N_2 + 2.46(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2 + dO_2$$

$$\begin{aligned}
&C: 0.65 + 0.25(2) = a \Rightarrow a = 1.15 \\
&H: 0.65(4) + 0.25(4) = 2b \Rightarrow b = 1.8 \\
&O: (2)d + 1.15(2) + 1.8 = 2(2.46) \Rightarrow d = 0.41 \\
&N: 0.1(2) + (2.46)(3.76)(2) = 2c \Rightarrow c = 9.35
\end{aligned}$$

Balanced reaction:

$$0.65CH_4 + 0.25C_2H_6 + 0.1N_2 + 2.46(O_2 + 3.76N_2) \rightarrow 1.15CO_2 + 1.8H_2O + 9.35N_2 + 0.41O_2$$

$$CH_4 + 0.38C_2H_6 + 0.15N_2 + 3.78(O_2 + 3.76N_2) \rightarrow 1.77CO_2 + 2.77H_2O + 14.38N_2 + 0.63O_2$$

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{3.78\,(4.76)\,(29)}{(16) + 0.38\,(28) + 0.15\,(28)} = 16.92\,\frac{\text{kg of air}}{\text{kg of fuel}}$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-24 [OJV] A dry analysis of products in the combustion of coal yields 9.7% CO_2, 0.5% CO, 2.95% O_2 and the rest N_2 by volume. (a) Determine the percent theoretical air (λ) used in the reaction and (b) the equivalent ratio (φ).

SOLUTION:

Theoretical reaction is:

$$\mathrm{C} + (\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow \mathrm{CO_2} + 3.76\mathrm{N_2}$$

$$\overline{\mathrm{AF}}_{\mathrm{th}} = \frac{n_{air}}{n_{fuel}} \Rightarrow \overline{\mathrm{AF}}_{\mathrm{th}} = \frac{1}{1} \Rightarrow \overline{\mathrm{AF}}_{\mathrm{th}} = 1$$

The actual reaction for burning of coal is:

$$a\mathrm{C} + b(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 9.7\mathrm{CO_2} + 0.5\mathrm{CO} + 2.95\mathrm{O_2} + d\mathrm{N_2}$$

Balancing the no. of moles of oxygen on both reactant and product side:

$$a = 9.7 + 0.5 \Rightarrow a = 10.2$$

$$b = 9.7 + \frac{0.5}{2} + 2.95 \Rightarrow b = 12.9$$

$$10.2\mathrm{C} + 12.9(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 9.7\mathrm{CO_2} + 0.5\mathrm{CO} + 2.95\mathrm{O_2} + 48.504\mathrm{N_2}$$

Normalizing the reaction;

$$\mathrm{C} + 1.26(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 0.95\mathrm{CO_2} + 0.04\mathrm{CO} + 0.29\mathrm{O_2} + 4.75\mathrm{N_2}$$

$$\overline{\mathrm{AF}}_{\mathrm{actual}} = \frac{n_{air}}{n_{fuel}} = \frac{1.26}{1} \Rightarrow \overline{\mathrm{AF}}_{\mathrm{actual}} = 1.26$$

$$\text{theoritical air}(\lambda) = \frac{\overline{\mathrm{AF}}_{\mathrm{actual}}}{\overline{\mathrm{AF}}_{\mathrm{th}}} \Rightarrow \lambda = 1.26$$

$$\%\ \text{theoritical air} = (1.26\ x\ 100) \Rightarrow \% = 126\%$$

$$\text{equivalent ratio } (\varphi) = \frac{1}{\lambda} \Rightarrow \varphi = 0.791$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-25 [OJQ] Carbon is burned with dry air. The volumetric analysis of the products produces 10.06 percent CO_2, 0.42 percent CO, and 10.69 percent O_2 (and the rest N_2). Determine (a) the air-fuel ratio on a mass basis, (b) the percentage of theoretical air (λ) used in the reaction, and (b) the equivalent ratio (φ).

SOLUTION:

For theoretical air we have the following reaction:

$$\mathrm{C} + (\mathrm{O_2} + 3.76\,\mathrm{N_2}) \rightarrow \mathrm{CO_2} + 3.76\mathrm{N_2}$$

Now a chemical balance must be performed two ways. The first is to balance the carbon as it was given:

$$a\mathrm{C} + \mathrm{b}(\mathrm{O_2} + 3.76\,\mathrm{N_2}) \rightarrow 10.06\mathrm{CO_2} + 0.42\mathrm{CO} + 10.69\mathrm{O_2} + 78.83\mathrm{N_2}$$

Balancing the reaction:

$$a = 10.06 + 0.42 = 10.48$$

$$2b = 2x10.06 + 0.42 + 2x10.69 \ \Rightarrow b = 20.96$$

The above yields the following:

$$10.48\mathrm{C} + 20.96(\mathrm{O_2} + 3.76\,\mathrm{N_2}) \rightarrow 10.06\mathrm{CO_2} + 1.019\mathrm{O_2} + 7.517\mathrm{N_2}$$

Dividing through by 10.48 to get in terms of a per fuel reaction:

$$\mathrm{C} + 2(\mathrm{O_2} + 3.76\,\mathrm{N_2}) \rightarrow 0.9593\mathrm{CO_2} + 0.4\mathrm{CO} + 1.019\mathrm{O_2} + 7.517\mathrm{N_2}$$

(a) Air-fuel ratio:

$$\mathrm{AF} = \frac{m_{air}}{m_{fuel}} = \frac{(20.96)(4.76)(29)}{(10.48)(12)} = 23 \ \frac{\text{kg of air}}{\text{kg of fuel}}$$

(b) This yields a percentage of theoretical air of:

$$\text{theoretical air}(\lambda) = \frac{\overline{\mathrm{AF}}_{\mathrm{actual}}}{\overline{\mathrm{AF}}_{\mathrm{th}}} \Rightarrow \lambda = 2 = 200\%$$

Alternatively, the above can be repeated with the same results balancing the following equation:

$$C + a(O_2 + 3.76\, N_2) \rightarrow b(10.06CO_2 + 0.42CO + 10.69O_2 + 78.83N_2)$$

Solving:

$a = 2$

$b = 0.0954$

This also implies that the theoretical air is 200%.

(c) Equivalence ratio:

$$\overline{\mathrm{AF}}_{\text{theoretical}} = \frac{m_{air}}{m_{fuel}} \Rightarrow \overline{\mathrm{AF}}_{\text{theoretical}} = \frac{(4.76)(29)}{12} = 11.5$$

$$\text{theoretical air}(\lambda) = \frac{\overline{\mathrm{AF}}_{\text{actual}}}{\overline{\mathrm{AF}}_{\text{th}}} \Rightarrow \lambda = 2$$

$$\text{equivalent ratio } (\varphi) = \frac{1}{\lambda} \Rightarrow \varphi = 0.5$$

TEST Verification: It is not possible to solve this question by TEST.

13-1-26 [OJY] Octane (C_8H_{18}) is burned with theoretical amount of air at a pressure of 500 kPa. Determine (a) the air fuel ratio on a mole basis, (b) the air fuel ratio on a mass basis, (c) If the products are cooled at a constant pressure of 100 kPa, at what temperature will dew start to form? (d) Suppose the products are cooled way below the dew point temperature so that all the water from the products are removed (neglect any vapor which may still be present at very low amount). What would be the volume fraction of CO_2 in the dry products? (e) If you have a smog test report of your gasoline burning car at hand, compare the CO_2 level of your analysis with the actual smog test result and discuss your finding.

SOLUTION:

$$\mathrm{C_8H_{18}} + a(\mathrm{O_2} + 3.76\,\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

To determine our coefficients, we can balance the numerical values:

$$b = 8; \quad 2c = 18 \Rightarrow c = 9; \quad 2a = 2b + c \Rightarrow a = 12.5$$
$$3.76a = d \Rightarrow d = 47$$

Since this is a stoichiometric reaction, we can directly write our final chemical equation:

$$\mathrm{C_8H_{18}} + 12.5(\mathrm{O_2} + 3.76\,\mathrm{N_2}) \rightarrow 8\mathrm{CO_2} + 9\mathrm{H_2O} + 47\mathrm{N_2}$$

(a) The AF ratio on a molar basis:

$$\overline{\mathrm{AF}} = \frac{12.5(1+3.76)}{1} = 59.5\,\frac{\text{kmol of air}}{\text{kmol of fuel}}$$

(b) To determine the AF ratio on a mass basis, we will use the molar mass of both the air and the fuel:

$$\mathrm{AF_{mass}} = \frac{\text{kmol air } x\ M_{air}}{\text{kmol fuel } x\ M_{fuel}} = 59.5\frac{29}{114.23} = 15.105\,\frac{\text{kg of air}}{\text{kg of fuel}}$$

(c) The dew point temperature is defined as:

$$T_{DP} = T_{sat@P_v}$$

Or the dew point temperature is the saturation temperature at the partial pressure of the vapor. In order to determine the partial pressure, we must determine the molar ratio of the H_2O:

$$y_{\mathrm{H_2O}} = \frac{\eta_{\mathrm{H_2O}}}{\eta_{mixture}} = \frac{P_V}{P_{total}} = \frac{9}{8+9+47} = 0.1406$$

This implies that the partial pressure of the vapor is:

$$P_V = y_{H_2O} \text{ x } P_{total} = (0.1406)100 = 14.06$$

From TEST with the found pressure and a quality of 1:

$$T_{DP} = T_{sat@P_v} = 52.6\ °C$$

(d) If all the water would be removed, we would now have the following species present in our products:

$$8CO_2 + 47N_2$$

The volume fraction can be determined from the mole fraction:

$$y_{CO_2} = \frac{\eta_{CO_2}}{\eta_{mixture}} = \frac{\nu_{CO_2}}{\nu_{total}} = \frac{8}{8+47} = 0.145$$

TEST Verification: Use the n-IG non-premixed open-steady combustion TESTcalc to verify the results.

13-1-27 [OJA] A coal sample has a mass analysis of 76.39% carbon, 4.2% hydrogen (H_2), 5.32% oxygen (O_2), 1.63% nitrogen (N_2), 1.5% sulfur and the rest is ash. For complete combustion with 120% of the theoretical air, determine the air-fuel ratio on a mass basis.

SOLUTION:

The coal sample per 100kg: 76.39 kg C, 4.2 kg H_2, 5.32 kg O_2, 1.63 kg N_2, 1.5 kg S, 10.96 kg ash. Ash is assumed to not participate in the reaction, but is included in the mass of the fuel.

Given the mass analysis of the coal sample, find the molar composition of 100 kg coal:

$$\left(\frac{76.39}{\bar{M}_{\mathrm{C}}}\right)\mathrm{C}+\left(\frac{4.2}{\bar{M}_{\mathrm{H_2}}}\right)\mathrm{H_2}+\left(\frac{5.32}{\bar{M}_{\mathrm{O_2}}}\right)\mathrm{O_2}+\left(\frac{1.63}{\bar{M}_{\mathrm{N_2}}}\right)\mathrm{N_2}+\left(\frac{1.5}{\bar{M}_{\mathrm{S}}}\right)\mathrm{S}$$

$$=6.37\mathrm{C}+2.1\mathrm{H_2}+0.166\mathrm{O_2}+0.0582\mathrm{N_2}+0.0469\mathrm{S}$$

The theoretical reaction is given by:

$$\left[6.37\mathrm{C}+2.1\mathrm{H_2}+0.166\mathrm{O_2}+0.0582\mathrm{N_2}+0.0469\mathrm{S}\right]+a\left(\mathrm{O_2}+3.76\mathrm{N_2}\right)$$
$$\rightarrow b\mathrm{CO_2}+c\mathrm{SO_2}+d\mathrm{H_2O}+e\mathrm{N_2}$$

The five atom balance equations are given by:

$$\begin{aligned}
&\mathrm{O}:\ 0.166(2)+a(2)=b(2)+c(2)+d(1)\\
&\mathrm{C}:\ 6.37(1)=b(1)\Rightarrow b=1\\
&\mathrm{H_2}:2.1(1)=d(1)\Rightarrow d=2.1\\
&\mathrm{S}:0.0469(1)=c(1)\Rightarrow c=0.0469\\
&\mathrm{N_2}:0.0582(1)+a(3.76)=e(1)\Rightarrow e=0.0582+a(3.76)
\end{aligned}$$

Solving for a and e:

$$a=\frac{6.37(2)+0.0469(2)+2.1(1)-0.166(2)}{2}=7.301;\quad e=0.0582+27.45=27.51$$

Therefore, the theoretical balanced reaction per 100kg of coal is:

$$\left[6.37\mathrm{C}+2.1\mathrm{H_2}+0.166\mathrm{O_2}+0.0582\mathrm{N_2}+0.0469\mathrm{S}\right]+7.301\left(\mathrm{O_2}+3.76\mathrm{N_2}\right)$$
$$\rightarrow 6.37\mathrm{CO_2}+0.0469\mathrm{SO_2}+2.1\mathrm{H_2O}+27.51\mathrm{N_2}$$

The air-fuel ratio is given by:

$$\frac{m_{air}}{m_f} = \frac{7.301(4.76)\bar{M}_{air}}{100\,\text{kg coal}} = \frac{7.301(4.76)(29\text{kg/kmol})}{100\,\text{kg coal}} \Rightarrow (\text{AF})_{th} = 10.08$$

To find the air-fuel ratio with 120% of the theoretical air, multiply $(\text{AF})_{\text{th}}$ by 1.20:

$$\text{AF} = (\text{AF})_{\text{th}}(1.20) = 10.05(1.20) = 12.06\ \frac{\text{kg of air}}{\text{kg of fuel}}$$

TEST Verification: It is not possible to solve this problem by TEST.

13-1-28 [OJS] A fuel mixture with the molar analysis 75% CH_4, 15% CO, 5% O_2 and 5% N_2 burns completely with 10% excess air in a reactor operating at steady state. If the molar flow rate of fuel is 0.2 kmol/h, determine the molar flow rate of air in kmol/h.

SOLUTION:

The theoretical reaction is expressed in terms of 1 kmol of fuel and unknown amounts (kmol) of air and products components.

$$0.75\mathrm{CH_4} + 0.15\mathrm{CO} + 0.05\mathrm{O_2} + 0.05\mathrm{N_2} + a(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow b\mathrm{CO_2} + c\mathrm{H_2O} + d\mathrm{N_2}$$

$$\mathrm{O}: a + 0.075 + 0.05 = b + \frac{c}{2}$$

$$\mathrm{C}: 0.75 + 0.15 = b,\ \ b = 0.9$$

$$\mathrm{N}: 0.05 + 3.76a = d$$

$$\mathrm{H}: c = 1.5$$

$$a = 0.9 + 0.75 - 0.075 - 0.05,\ \ a = 1.525$$

$$d = 5.784$$

Solving, the theoretical reaction can be written as:

$$0.75\mathrm{CH_4} + 0.15\mathrm{CO} + 0.05\mathrm{O_2} + 0.05\mathrm{N_2} + 1.525(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 0.9\mathrm{CO_2} + 1.5\mathrm{H_2O} + 5.784\mathrm{N_2}$$

The molar-based air-fuel ratio now can be obtained from the equation above

$$\left(\overline{\mathrm{AF}}\right)_{th} = \frac{n_{air}}{n_{fuel}} = \frac{1.525 \times 4.76}{1} = 7.259 \frac{\text{mole of air}}{\text{mole of fuel}}$$

For 110% theoretical air (10% excess air), the air fuel ratio is:

$$\left(\overline{\mathrm{AF}}\right) = 1.1\left(\overline{\mathrm{AF}}\right)_{th} = 1.1 \times 7.259 = 7.985 \frac{\text{mole of air}}{\text{mole of fuel}}$$

Therefore Molar Flow rate of air in kmol/h is:

$$\dot{\mathrm{M}}_{\mathrm{air}} = \left(\overline{\mathrm{AF}}\right)\dot{\mathrm{M}}_{\mathrm{F}} = 7.985 \times 0.2 = 1.598 \frac{\mathrm{kmol}}{\mathrm{h}}$$

TEST Verification: It is not possible to solve it by TEST.