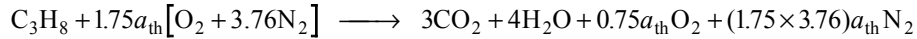


**14-14** Propane is burned with 75 percent excess air during a combustion process. The AF ratio is to be determined.

**Assumptions** 1 Combustion is complete. 2 The combustion products contain CO<sub>2</sub>, H<sub>2</sub>O, O<sub>2</sub>, and N<sub>2</sub> only.

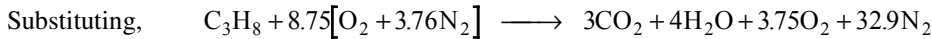
**Properties** The molar masses of C, H<sub>2</sub>, and air are 12 kg/kmol, 2 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

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



where  $a_{\text{th}}$  is the stoichiometric coefficient for air. We have automatically accounted for the 75% excess air by using the factor  $1.75a_{\text{th}}$  instead of  $a_{\text{th}}$  for air. The stoichiometric amount of oxygen ( $a_{\text{th}}\text{O}_2$ ) will be used to oxidize the fuel, and the remaining excess amount ( $0.75a_{\text{th}}\text{O}_2$ ) will appear in the products as free oxygen. The coefficient  $a_{\text{th}}$  is determined from the O<sub>2</sub> balance,

$$\text{O}_2 \text{ balance: } 1.75a_{\text{th}} = 3 + 2 + 0.75a_{\text{th}} \longrightarrow a_{\text{th}} = 5$$



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

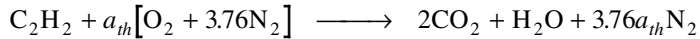
$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{(8.75 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{(3 \text{ kmol})(12 \text{ kg/kmol}) + (4 \text{ kmol})(2 \text{ kg/kmol})} = \mathbf{27.5 \text{ kgair/kgfuel}}$$

**14-15** Acetylene is burned with the stoichiometric amount of air during a combustion process. The AF ratio is to be determined on a mass and on a mole basis.

**Assumptions** 1 Combustion is complete. 2 The combustion products contain CO<sub>2</sub>, H<sub>2</sub>O, and N<sub>2</sub> only.

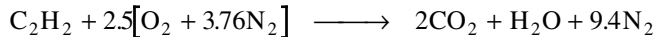
**Properties** The molar masses of C, H<sub>2</sub>, and air are 12 kg/kmol, 2 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

**Analysis** This is a theoretical combustion process since C<sub>2</sub>H<sub>2</sub> is burned completely with stoichiometric amount of air. The stoichiometric combustion equation of C<sub>2</sub>H<sub>2</sub> is



$$\text{O}_2 \text{ balance: } a_{\text{th}} = 2 + 0.5 \longrightarrow a_{\text{th}} = 2.5$$

Substituting,

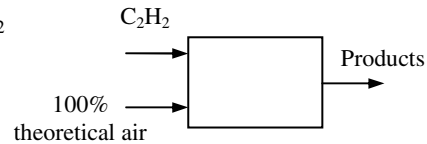


The air-fuel ratio is determined by taking the ratio of the mass of the air to the mass of the fuel,

$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{(2.5 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{(2 \text{ kmol})(12 \text{ kg/kmol}) + (1 \text{ kmol})(2 \text{ kg/kmol})} = \mathbf{13.3 \text{ kgair/kgfuel}}$$

On a mole basis, the air-fuel ratio is expressed as the ratio of the mole numbers of the air to the mole numbers of the fuel,

$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{2.5 \times 4.76 \text{ kmol}}{1 \text{ kmol fuel}} = \mathbf{11.9 \text{ kmol air / kmol fuel}}$$



**14-19** Octane is burned with 250 percent theoretical air during a combustion process. The AF ratio and the dew-point temperature of the products 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. **3** Combustion gases are ideal gases.

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

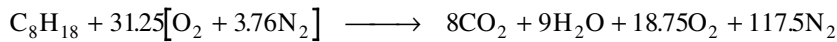
**Analysis** (a) The combustion equation in this case can be written as



where  $a_{\text{th}}$  is the stoichiometric coefficient for air. It is determined from

$$\text{O}_2 \text{ balance: } 2.5a_{\text{th}} = 8 + 4.5 + 1.5a_{\text{th}} \longrightarrow a_{\text{th}} = 12.5$$

Substituting,



Thus,

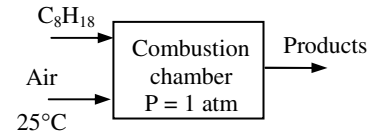
$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{(31.25 \times 4.76 \text{ kmol})(29 \text{ kg/kmol})}{(8 \text{ kmol})(12 \text{ kg/kmol}) + (9 \text{ kmol})(2 \text{ kg/kmol})} = \mathbf{37.8 \text{ kgair/kgfuel}}$$

(b) The dew-point temperature of a gas-vapor mixture is the saturation temperature of the water vapor in the product gases corresponding to its partial pressure. That is,

$$P_v = \left( \frac{N_v}{N_{\text{prod}}} \right) P_{\text{prod}} = \left( \frac{9 \text{ kmol}}{153.25 \text{ kmol}} \right) (101.325 \text{ kPa}) = 5.951 \text{ kPa}$$

Thus,

$$T_{dp} = T_{\text{sat}@5.951 \text{ kPa}} = \mathbf{35.7^\circ\text{C}}$$

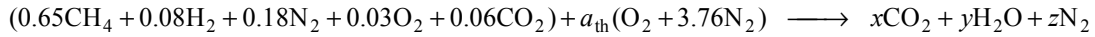


**14-24** The volumetric fractions of the constituents of a certain natural gas are given. The AF ratio is to be determined if this gas is burned with the stoichiometric amount of dry air.

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

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

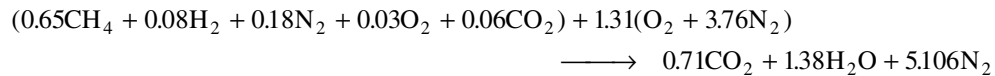
**Analysis** Considering 1 kmol of fuel, the combustion equation can be written as



The unknown coefficients in the above equation are determined from mass balances,

$$\begin{array}{llll} \text{C:} & 0.65 + 0.06 = x & \longrightarrow & x = 0.71 \\ \text{H:} & 0.65 \times 4 + 0.08 \times 2 = 2y & \longrightarrow & y = 1.38 \\ \text{O}_2: & 0.03 + 0.06 + a_{\text{th}} = x + y / 2 & \longrightarrow & a_{\text{th}} = 1.31 \\ \text{N}_2: & 0.18 + 3.76a_{\text{th}} = z & \longrightarrow & z = 5.106 \end{array}$$

Thus,



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

$$\begin{aligned} m_{\text{air}} &= (1.31 \times 4.76 \text{ kmol})(29 \text{ kg/kmol}) = 180.8 \text{ kg} \\ m_{\text{fuel}} &= (0.65 \times 16 + 0.08 \times 2 + 0.18 \times 28 + 0.03 \times 32 + 0.06 \times 44) \text{ kg} = 19.2 \text{ kg} \end{aligned}$$

and

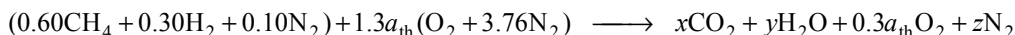
$$\text{AF}_{\text{th}} = \frac{m_{\text{air, th}}}{m_{\text{fuel}}} = \frac{180.8 \text{ kg}}{19.2 \text{ kg}} = \mathbf{9.42 \text{ kg air / kg fuel}}$$

**14-26** The composition of a gaseous fuel is given. It is burned with 130 percent theoretical air. The AF ratio and the fraction of water vapor that would condense if the product gases were cooled 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 C,  $\text{H}_2$ ,  $\text{N}_2$ , and air are 12 kg/kmol, 2 kg/kmol, 28 kg/kmol, and 29 kg/kmol, respectively (Table A-1).

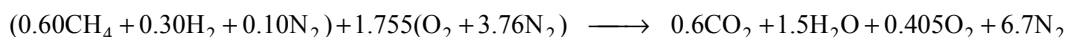
**Analysis** (a) The fuel is burned completely with excess air, and thus the products will contain  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{N}_2$ , and some free  $\text{O}_2$ . Considering 1 kmol of fuel, the combustion equation can be written as



The unknown coefficients in the above equation are determined from mass balances,

$$\begin{array}{llll} \text{C:} & 0.60 = x & \longrightarrow & x = 0.60 \\ \text{H:} & 0.60 \times 4 + 0.30 \times 2 = 2y & \longrightarrow & y = 1.50 \\ \text{O}_2: & 1.3a_{\text{th}} = x + y/2 + 0.3a_{\text{th}} & \longrightarrow & a_{\text{th}} = 1.35 \\ \text{N}_2: & 0.10 + 3.76 \times 1.3a_{\text{th}} = z & \longrightarrow & z = 6.70 \end{array}$$

Thus,



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

$$\begin{aligned} m_{\text{air}} &= (1.755 \times 4.76 \text{ kmol})(29 \text{ kg/kmol}) = 242.3 \text{ kg} \\ m_{\text{fuel}} &= (0.6 \times 16 + 0.3 \times 2 + 0.1 \times 28) \text{ kg} = 13.0 \text{ kg} \end{aligned}$$

and

$$\text{AF}_{\text{th}} = \frac{m_{\text{air, th}}}{m_{\text{fuel}}} = \frac{242.3 \text{ kg}}{13.0 \text{ kg}} = \mathbf{18.6 \text{ kg air / kg fuel}}$$

(b) For each kmol of fuel burned,  $0.6 + 1.5 + 0.405 + 6.7 = 9.205$  kmol of products are formed, including 1.5 kmol of  $\text{H}_2\text{O}$ . Assuming that the dew-point temperature of the products is above  $20^\circ\text{C}$ , some of the water vapor will condense as the products are cooled to  $20^\circ\text{C}$ . If  $N_w$  kmol of  $\text{H}_2\text{O}$  condenses, there will be  $1.5 - N_w$  kmol of water vapor left in the products. The mole number of the products in the gas phase will also decrease to  $9.205 - N_w$  as a result. Treating the product gases (including the remaining water vapor) as ideal gases,  $N_w$  is determined by equating the mole fraction of the water vapor to its pressure fraction,

$$\frac{N_w}{N_{\text{prod, gas}}} = \frac{P_w}{P_{\text{prod}}} \longrightarrow \frac{1.5 - N_w}{9.205 - N_w} = \frac{2.339 \text{ kPa}}{101.325 \text{ kPa}} \longrightarrow N_w = 1.32 \text{ kmol}$$

since  $P_w = P_{\text{sat @ } 20^\circ\text{C}} = 2.339 \text{ kPa}$ . Thus the fraction of water vapor that condenses is  $1.32/1.5 = 0.88$  or **88%**.

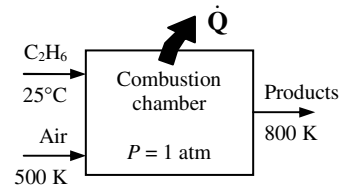
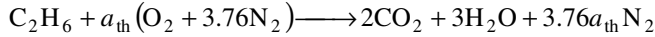
**14-27 EES** solution of this (and other comprehensive problems designated with the *computer icon*) is available to instructors at the *Instructor Manual* section of the *Online Learning Center* (OLC) at [www.mhhe.com/cengel-boles](http://www.mhhe.com/cengel-boles). See the Preface for access information.

**14-57** Ethane gas is burned with stoichiometric amount of air during a steady-flow combustion process. The rate of heat transfer from the combustion chamber is to be determined.

**Assumptions** 1 Steady operating conditions exist. 2 Air and combustion gases are ideal gases. 3 Kinetic and potential energies are negligible. 4 Combustion is complete.

**Properties** The molar mass of  $C_2H_6$  is 30 kg/kmol (Table A-1).

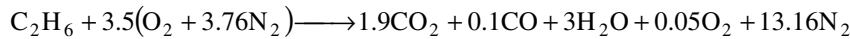
**Analysis** The theoretical combustion equation of  $C_2H_6$  is



where  $a_{th}$  is the stoichiometric coefficient and is determined from the  $O_2$  balance,

$$a_{th} = 2 + 1.5 = 3.5$$

Then the actual combustion equation can be written as



The heat transfer for this combustion process is determined from the energy balance  $E_{in} - E_{out} = \Delta E_{system}$  applied on the combustion chamber with  $W = 0$ . It reduces to

$$-Q_{out} = \sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P - \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R$$

Assuming the air and the combustion products to be ideal gases, we have  $h = h(T)$ . From the tables,

Substance	$\bar{h}_f^\circ$ kJ/kmol	$\bar{h}_{500\text{ K}}$ kJ/kmol	$\bar{h}_{298\text{ K}}$ kJ/kmol	$\bar{h}_{800\text{ K}}$ kJ/kmol
$C_2H_6(g)$	-84,680	---	---	---
$O_2$	0	14,770	8682	24,523
$N_2$	0	14,581	8669	23,714
$H_2O(g)$	-241,820	---	9904	27,896
CO	-110,530	---	8669	23,844
$CO_2$	-393,520	---	9364	32,179

Thus,

$$\begin{aligned} -Q_{out} &= (1.9)(-393,520 + 32,179 - 9364) + (0.1)(-110,530 + 23,844 - 8669) \\ &\quad + (3)(-241,820 + 27,896 - 9904) + (0.05)(0 + 24,523 - 8682) + (13.16)(0 + 23,714 - 8669) \\ &\quad - (1)(-84,680 + h_{298} - h_{298}) - (3.5)(0 + 14,770 - 8682) - (13.16)(0 + 14,581 - 8669) \\ &= -1,201,005 \text{ kJ / kmol } C_2H_6 \end{aligned}$$

or  $Q_{out} = 1,201,005 \text{ kJ / kmol } C_2H_6$

Then the rate of heat transfer for a mass flow rate of 3 kg/h for the ethane becomes

$$\dot{Q}_{out} = \dot{N}Q_{out} = \left( \frac{\dot{m}}{N} \right) Q_{out} = \left( \frac{3 \text{ kg/h}}{30 \text{ kg/kmol}} \right) (1,201,005 \text{ kJ/kmol}) = \mathbf{200,170 \text{ kJ/h}}$$

**Adiabatic Flame Temperature**

**14-63C** For the case of stoichiometric amount of pure oxygen since we have the same amount of chemical energy released but a smaller amount of mass to absorb it.

**14-64C** Under the conditions of complete combustion with stoichiometric amount of air.

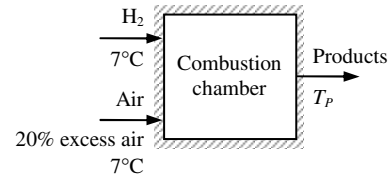
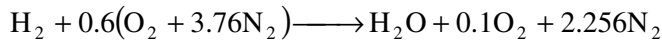
**14-65** [Also solved by EES on enclosed CD] Hydrogen is burned with 20 percent excess air during a steady-flow combustion process. The exit temperature of product gases is to be determined.

**Assumptions 1** Steady operating conditions exist. **2** Air and combustion gases are ideal gases. **3** Kinetic and potential energies are negligible. **4** There are no work interactions. **5** The combustion chamber is adiabatic.

**Analysis** Adiabatic flame temperature is the temperature at which the products leave the combustion chamber under adiabatic conditions ( $Q = 0$ ) with no work interactions ( $W = 0$ ). Under steady-flow conditions the energy balance  $E_{in} - E_{out} = \Delta E_{system}$  applied on the combustion chamber reduces to

$$\sum N_P (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_P = \sum N_R (\bar{h}_f^\circ + \bar{h} - \bar{h}^\circ)_R$$

The combustion equation of H<sub>2</sub> with 20% excess air is



From the tables,

Substance	$\bar{h}_f^\circ$ kJ/kmol	$\bar{h}_{280\text{ K}}$ kJ/kmol	$\bar{h}_{298\text{ K}}$ kJ/kmol
H <sub>2</sub>	0	7945	8468
O <sub>2</sub>	0	8150	8682
N <sub>2</sub>	0	8141	8669
H <sub>2</sub> O (g)	-241,820	9296	9904

Thus,

$$(1)(-241,820 + \bar{h}_{\text{H}_2\text{O}} - 9904) + (0.1)(0 + \bar{h}_{\text{O}_2} - 8682) + (2.256)(0 + \bar{h}_{\text{N}_2} - 8669) = (1)(0 + 7945 - 8468) + (0.6)(0 + 8150 - 8682) + (2.256)(0 + 8141 - 8669)$$

It yields  $\bar{h}_{\text{H}_2\text{O}} + 0.1\bar{h}_{\text{O}_2} + 2.256\bar{h}_{\text{N}_2} = 270,116 \text{ kJ}$

The adiabatic flame temperature is obtained from a trial and error solution. A first guess is obtained by dividing the right-hand side of the equation by the total number of moles, which yields  $270,116 / (1 + 0.1 + 2.256) = 80,488 \text{ kJ/kmol}$ . This enthalpy value corresponds to about 2400 K for N<sub>2</sub>. Noting that the majority of the moles are N<sub>2</sub>,  $T_p$  will be close to 2400 K, but somewhat under it because of the higher specific heat of H<sub>2</sub>O.

At 2300 K:  $\bar{h}_{\text{H}_2\text{O}} + 0.1\bar{h}_{\text{O}_2} + 2.256\bar{h}_{\text{N}_2} = (1)(98,199) + (0.1)(79,316) + (2.256)(75,676) = 276,856 \text{ kJ}$  (Higher than 270,116 kJ)

At 2250 K:  $\bar{h}_{\text{H}_2\text{O}} + 0.1\bar{h}_{\text{O}_2} + 2.256\bar{h}_{\text{N}_2} = (1)(95,562) + (0.1)(77,397) + (2.256)(73,856) = 269,921 \text{ kJ}$  (Lower than 270,116 kJ)

By interpolation,  $T_p = 2251.4 \text{ K}$