Lecture Seven

Theoretical and Actual Combustion Processes

A combustion process is **complete** if all the carbon in the fuel burns to CO_2 and all the hydrogen burns to H_2O. That is, all the combustible components of a fuel are burned to completion during a complete combustion process. Conversely, the combustion process is **incomplete** if the combustion products contain any unburned fuel or components such as C, H_2, CO or OH.

Insufficient oxygen is an obvious reason for incomplete combustion, but it is not the only one. Incomplete combustion occurs even when more oxygen is present in the combustion chamber than is needed for complete combustion. This may be attributed to insufficient mixing in the combustion chamber during the limited time that the fuel and the oxygen are in contact. Another cause of incomplete combustion is dissociation, which becomes important at high temperatures.

The minimum amount of air needed for the complete combustion of a fuel is called the **stoichiometric** or **theoretical air**. Thus, when a fuel is completely burned with theoretical air, no uncombined oxygen is present in the product gases. The theoretical air is also referred to as the chemically correct amount of air, or 100 percent theoretical air. A combustion process with less than the theoretical air is bound to be incomplete. The ideal combustion process during which a fuel is burned completely with theoretical air is called the **stoichiometric** or **theoretical combustion** of that fuel.

In actual combustion processes, it is common practice to use more air than the stoichiometric amount to increase the chances of complete combustion or to control the temperature of the combustion chamber. The amount of air in excess of the stoichiometric amount is called **excess air**. The amount of excess air is usually expressed in terms of the stoichiometric air as **percent excess air** or **percent theoretical air**. The amount of air used in combustion processes is also expressed in terms of the **equivalence ratio**, which is the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio.

Example (7.6): Determine the air-fuel ratio, when ethane C_2H_6 is burned with 20 percent excess air during a combustion process. The molar masses of air and ethane are 29 and 30 kg/kmol, respectively.

Solution:

The chemical reaction of ethane with 20% excess air is:

$$C_2H_6 + 1.2xO_2 + 1.2 \times 3.76xN_2 \rightarrow yCO_2 + zH_2O + 0.2xO_2 + 1.2 \times 3.76xN_2$$

Balancing the two sides of the equation:

Carbon (C): $2 = y$

Hydrogen (H_2): $6 = 2z \rightarrow z = 3$

Oxygen (O_2): $2 \times 1.2x = 2y + z + 2 \times 0.2x \rightarrow 2.4x = 2 \times 2 + 3 + 0.4x \rightarrow x = 3.5$

Then, the reaction equation becomes:

$$C_2H_6 + 4.2O_2 + 15.79N_2 \rightarrow 2CO_2 + 3H_2O + 0.7O_2 + 15.79N_2$$

The air-fuel ratio on mass basis is:

$$AF = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{N_{\text{air}}M_{\text{air}}}{N_{\text{fuel}}M_{\text{fuel}}} = \frac{(4.2 + 15.79) \times 29}{1 \times 30} = 19.93 \text{ kg air/kg fuel}$$

Example (7.7): Methane CH_4 is burned with atmospheric air. The analysis of the products on a dry basis is as follows: 10% CO_2, 0.53% CO, 2.37% O_2 and 87.1% N_2. Determine the combustion equation then find the percent theoretical air.

Solution:

The chemical reaction is:

$$aCH_4 + bO_2 + cN_2 \rightarrow 10CO_2 + 0.53CO + 2.37O_2 + dH_2O + 87.1N_2$$

Balancing the two sides of the equation:

Nitrogen (N_2): $c = 87.1$

Since the nitrogen comes from the air:

$$c = b \times 3.76 \rightarrow b = \frac{c}{3.76} = \frac{87.1}{3.76} = 23.16$$

Carbon (C): $a = 10 + 0.53 \rightarrow a = 10.53$

Hydrogen (H_2): $4a = 2d \rightarrow d = 2 \times 10.53 = 21.06$

Then, the reaction equation becomes:

$$10.53CH_4 + 23.16O_2 + 87.1N_2 \rightarrow 10CO_2 + 0.53CO + 2.37O_2 + 21.06H_2O + 87.1N_2$$

Dividing by 10.53 yields the combustion equation per kmol of fuel:

$$CH_4 + 2.2O_2 + 8.27N_2 \rightarrow 0.95CO_2 + 0.05CO + 0.225O_2 + 2H_2O + 8.27N_2$$

To find the percentage of theoretical air used, we need to know the theoretical amount of air, which is determined from the theoretical combustion equation of the fuel as follows:

$$CH_4 + xO_2 + 3.76xN_2 \rightarrow yCO_2 + zH_2O + 3.76xN_2$$

Balancing the two sides of the equation:

Carbon (C): $1 = y$

Hydrogen (H_2): $4 = 2z \rightarrow z = 2$

Oxygen (O_2): $2x = 2y + z \rightarrow 2x = 2 \times 1 + 2 \rightarrow x = 2$

Then, the reaction equation becomes:

$$CH_4 + 2O_2 + 7.52N_2 \rightarrow CO_2 + 2H_2O + 7.52N_2$$

Then:

$$\text{Percentage of theoretical air} = \frac{m_{\text{air,act}}}{m_{\text{air,th}}} = \frac{N_{\text{air,act}}}{N_{\text{air,th}}} = \frac{2.2 + 8.27}{2 + 7.52} \times 100\% = 110\%$$