Chapter 3: Fuel and Combustion

5.1 FUEL: can be defined as any material that liberates thermal energy by chemical reaction.

There are many kinds of fuel. The chemical reaction release thermal energy from fuel is called **COMBUSTION**. During combustion the energy is released by oxidation of fuel elements such as carbon C, hydrogen H_2 and sulfur S, i.e. high temperature chemical reaction of these elements with oxygen O_2 (generally from air) releases energy to produce high temperature gases. These high temperature gases act as heat source.

5.2 Types of Fuels

1. **Solid fuel:** Coal is the most common solid fuel. Coal is a dark brown/black sedimentary rock.
2. **Liquid fuel:** Fuels in liquid form are called liquid fuels. Liquid fuels are generally obtained from petroleum and its by-products. These liquid fuels are complex mixture of different hydrocarbons, and obtained by refining the crude petroleum oil. Commonly used liquid fuels are petrol, kerosene diesel, aviation fuel, light fuel oil, heavy fuel oil etc.

Advantage of Liquid Fuel:

- Require less space for storage.
- Higher calorific value.
- They have nearly constant calorific value
- Easy handling and transportation.
- More clean that the solid fuel type.
- No ash problem.

Disadvantages of Liquid Fuel:

- Higher cost.
- Greater risk of fire
- Costly containers are required for storage and transport.

3. **Gaseous fuels:** These are the fuels in gaseous phase. Gaseous fuels are also generally hydrocarbon fuels derived from petroleum reserves available in nature. Most common gaseous fuel is natural gas. Gaseous fuels may also be produced artificially from burning solid fuel (coal) and water.

Advantages of Gaseous Fuel:

- Better control of combustion.
- Much less excess air is needed for complete combustion.
- Economy in fuel and more efficiency of furnace operation.
- Cleanest of all type of fuels.
- Gaseous fuels give economy of heat and produce higher temperatures (as they can be preheated in regenerative furnaces and thus heat from hot flue gases can be recovered).
- It is free from ash and mixes well with air to undergo complete combustion producing very little smoke.

Disadvantages of Gaseous Fuel:

- It is flammable.
- They require large storage capacity.

The fuel may be classified as primary fuel and secondary fuel according to existence in the nature, where the primary fuel was natural material used as a fuel. The secondary fuel is the artificial fuel refer to the prepared of fuel.

5.3 Requirements of a Good Fuel

The requirements of a good fuel are:

1. A good fuel should have a low ignition point.
2. It should have a high calorific value.
3. High burning efficiency.
4. It should not produce harmful gases.
5. It should produce least quantity of smoke (ash) and gases.
6. It should be economical (cheaper)
7. Easy to store and convenient for transportation.

Combustion

Combustion Reaction: when the bonds within molecules of the reactants are broken, atoms and electrons rearranged to form products. It is exothermic reaction.

In combustion reactions, rapid oxidation of combustible elements of the fuel results in energy release as combustion products are formed. The three major combustible chemical elements in most common fuels are carbon, hydrogen, and sulfur. Sulfur is usually a relatively unimportant contributor in the energy released, but it can be a significant cause of pollution and corrosion problems.

Combustion is **complete** when all the carbon present in the fuel is burned to carbon dioxide CO_2 all the hydrogen is burned to water H_2O, all the sulfur is burned to sulfur dioxide SO_2 , and all other combustible elements are fully oxidized. When these conditions are not fulfilled, combustion is incomplete.

The combustion reactions can be expressed by chemical equations of the form

$$Reactants \rightarrow Products$$

or

$$Fuel + Oxidizer \rightarrow Products$$

When dealing with chemical reactions, it is necessary to remember that the mass is conserved, so the mass of the products equals the mass of the reactants. The total mass of each chemical element must be the same on both sides of the equation, even though the elements exist in different chemical compounds in the reactants and products. However, the number of moles of products may differ from the number of moles of reactants. For example, consider the complete combustion of hydrogen with oxygen

$$\boldsymbol{H_2 + \frac{1}{2}O_2 \rightarrow H_2O}$$

In this case, the reactants are hydrogen and oxygen. Hydrogen is the fuel and oxygen is the oxidizer. Water is the only product of the reaction. The numerical coefficients in the equation, which precede the chemical symbols to give equal amounts of each chemical element on both sides of the equation, are called **stoichiometric coefficients**.

$$1\ kmol.\, H_2 + \frac{1}{2} kmol\ O_2 \rightarrow 1\ kmol\ H_2O$$

The total numbers of moles on the left and right sides of the above equation are not equal However, because mass is conserved; the total mass of reactants must equal the total mass of products. Since 1 kmol. of H_2, equals 2 kg, (1/2) kmol of O_2 equals 16 kg, and 1 kmol of H_2O equals 18 kg.

$$2kg\ H_2 + 16\ kg\ O_2 \rightarrow 18\ kg\ H_2O$$

Combustion Reactions

Combustion is the high temperature oxidation of the combustible elements of a fuel with heat release. The combustible elements in coal and fuel oil are carbon, hydrogen and sulfur. The basic chemical equations for complete combustion are

$$C + O_2 \rightarrow CO_2$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$S + O_2 \rightarrow SO_2$$

When insufficiently oxygen is present, the carbon will be burned incompletely with the formulation of carbon monoxide.

$$2C + O_2 \rightarrow 2CO$$

In order to BURNT a FUEL COMPLETELY, four basic conditions must be fulfilled:

1. Supply enough air for complete combustion of fuel.
2. Secure enough turbulence for thorough mixing of fuel and air.
3. Maintain a furnace temperature high enough to ignite the incoming fuel air mixture.
4. Provide a furnace volume large enough to allow time for combustion to be completed.

Oxygen is required in every combustion reaction. Pure oxygen is used only in special applications such as cutting and welding. In most combustion applications, air provides the needed oxygen.

For the combustion calculations the following assumptions are used for simplicity:

- All components of dry air other than oxygen are lumped together with nitrogen. Accordingly, air is considered to be 21% oxygen and 79% nitrogen on a molar basis. With this idealization the molar ratio of the nitrogen to the oxygen is **[0.79/0.21 = 3.76]**. When air supplies the oxygen in a combustion reaction, therefore, every mole of oxygen is accompanied by 3.76 moles of nitrogen.

- We also assume that the nitrogen present in the combustion air does not undergo chemical reaction. That is, nitrogen is regarded as inert. The nitrogen in the products is at the same temperature as the other products, however.

Accordingly, nitrogen undergoes a change of state if the products are at a temperature other than the reactant air temperature. If a high enough product temperature is attained, nitrogen can form compounds such as nitric oxide and nitrogen dioxide. Even trace amounts of oxides of nitrogen appearing in the exhaust of internal combustion engines can be a source of air pollution.

5.4 Calorific (Heating) Value of Fuel

It is defined as the heat liberated in kJ by complete combustion of 1 kg of fuel (solid or liquid). For gaseous fuels, the normal practice is to express calorific value in kJ/m^3. Calorific value is further classified as (i) Higher Heating Value (HHV) and (ii) Lower Heating Value (LHV).

Higher heating value (HHV) of fuel is the enthalpy (heat) of combustion when all the water (H_2O) formed during combustion is in liquid phase.

Lower heating value (LHV) of fuel refers to the enthalpy (heat) of combustion when all the water (H_2O) formed during combustion is in vapor form. The lower heating value will be less than higher heating value by the amount of heat required for evaporation of water.

$$HHV = LHV + (Heat\ required\ for\ evaporation\ of\ water)$$

5.5 Air Fuel Ratio

The **air–fuel ratio** is simply the ratio of the amount of air in a reaction (combustion) to the amount of fuel. The ratio can be written on a molar basis (moles of air divided by moles of fuel) or on a mass basis (mass of air divided by mass of fuel). Conversion between these values is accomplished using the molecular weights of the air, M_{air}, and fuel, M_{fuel}. For the combustion calculations the molecular weight of air is taken as 28.97 kg/kmol. Tables (5-1) provide the molecular weights of several important elements.

$$AF = \frac{mass\ of\ air}{mass\ of\ fuel} = \frac{M_{air} \times N_{air}}{M_{fuel} \times N_{fuel}}$$

Theoretical air-fuel ratio can be estimated from stoichiometric combustion analysis for just complete combustion.

Theoretical air: Theoretical amount of air refers to the minimum amount of air that is required for providing sufficient oxygen for complete combustion of fuel.

Table (5.1): Symbols with atomic mass and molecular mass.

Substance	Symbol	Atomic mass	Molecular mass(kg/kmol)
Hydrogen	H_2	1	2
Oxygen	O_2	16	32
Nitrogen	N_2	14	28
Carbon	C	12	12
sulfur	S	32	32

5.6. Theoretical and Actual Combustion Processes

It is often useful to study the combustion of a fuel by assuming that the combustion is complete. A combustion process is **complete** if all the carbon in the fuel burns to CO_2, all the hydrogen burns to H_2O, and all the sulfur (if any) burns to SO_2. That is, all the combustible components of a fuel are burned to completion during a complete combustion process.

Stoichiometric air: it is the minimum amount of air needed for the complete combustion of a fuel it is so called the **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 % theoretical air. A combustion process with less than the theoretical air is lead to incomplete combustion. The ideal combustion process during which a fuel is burned completely with theoretical air is called the stoichiometric or theoretical combustion of that fuel. For example, the theoretical combustion of methane is;

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

Notice that the products of the theoretical combustion contain no unburned methane and no C, H_2, CO, OH, or free O_2.

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**. For example, 50 % excess air is equivalent to 150 % theoretical air, and 200 % excess air is equivalent to 300 % theoretical air.

Of course, the stoichiometric air can be expressed as 0 % excess air or 100 % theoretical air. Amounts of air less than the stoichiometric amount are called **deficiency of air** and are often expressed as **percent deficiency of air**. For example, 90 % theoretical air is equivalent to 10 % deficiency of 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.

$$\text{equivalence ratio} = \frac{AF_{actual}}{AF_{theoretical}}$$

Example (5.1) One kmol of octane (C_8H_{18}) is burned with air that contains 20 kmol of air. Assuming the products contain only CO_2, H_2O, O_2, and N_2, determine the mole number of each gas in the products and the air–fuel ratio for this combustion process.

Solution:

The chemical equation for this combustion process can be written as

$$C_8H_{18} + 20(O_2 + 3.76N_2) \rightarrow xCO_2 + yH_2O + zO_2 + wN_2$$

Where the terms in the parentheses represent the composition of dry air that contains 1 kmol of O2 and *x*, *y*, *z*, and *w* represent the unknown mole numbers of the gases in the products. These unknowns are determined by applying the mass balance to each of the elements—that is, by requiring that the total mass or mole number of each element in the reactants be equal to that in the products:

C: $8 = x \rightarrow x = 8$

H: $18 = 2y \rightarrow y = 9$

O: $20 \times 2 = 2x + y + 2z \rightarrow z = 7.5$

N: $(20) \times (3.76) = w \rightarrow w = 75.2$

Substituting yields;

$$C_8H_{18} + 20(O_2 + 3.76N_2) \rightarrow 8CO_2 + 9H_2O + 7.5O_2 + 75.2N_2$$

Note that the coefficient 20 in the balanced equation above represents the number of moles of oxygen, not the number of moles of air. The latter is obtained by adding 20 × 3.76 = 75.2 moles of nitrogen to the 20 moles of oxygen, giving a total of 95.2 moles of air. The air–fuel ratio (AF) is determined by taking the ratio of the mass of the air and the mass of the fuel,

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{(NM)_{air}}{(NM)_{fuel}} = \frac{(NM)_{air}}{(NM)_C + (NM)_{H2}}$$

$$AF = \frac{(20 \times 4.76kmol) \times (29\, kg/kmol)}{(8kmol) \times (12\, kg/kmol) + (9kmol) \times (2\, kg/kmol)}$$

$AF = 24.2 \ kg\ air/kg\ fuel$

That is, 24.2 kg of air is used to burn each kilogram of fuel during this combustion process.

ans.[A/F=13.3 kg air/kg fuel, CO_2=13.6%, H_2O=12.2%, N_2=74.2%]