UNIT 5: FUELS AND COMBUSTION


5.1 INTRODUCTION

Fuel may be chemical or nuclear. Here we shall consider briefly chemical fuels only. A chemical fuel is a substance which releases heat energy on combustion. The principal combustible elements of each fuel are carbon and hydrogen. Though sulphur is a combustible element too but its presence in the fuel is considered to be undesirable.

In a chemical reaction the terms, reactants and the products are frequently used. ‘Reactants’ comprise of initial constituents which start the reaction while ‘products’ comprise of final constituents which are formed by the chemical reaction.

5.2. CLASSIFICATION OF FUELS

Fuels can be classified according to whether:
1. They occur in nature called primary fuels or are prepared called secondary fuels;
2. They are in solid, liquid or gaseous state.

The detailed classification of fuels can be given in a summary form as follows:

<table>
<thead>
<tr>
<th>TYPE OF FUEL</th>
<th>NATURAL (PRIMARY)</th>
<th>PREPARED (SECONDARY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Wood, Peat, Lignite coal</td>
<td>Coke, Charcoal, Briquettes</td>
</tr>
<tr>
<td>Liquid</td>
<td>Petroleum</td>
<td>Gasoline, Kerosene, Fuel oil, Alcohol, Benzol, Shale oil</td>
</tr>
<tr>
<td>Gas</td>
<td>Natural gas</td>
<td>Petroleum gas, Producer gas, Coal gas, Coke-oven gas, Blast furnace gas, Carburetted gas, Sewer gas</td>
</tr>
</tbody>
</table>
5.3 BASIC CHEMISTRY

Atoms. It is not possible to divide the chemical elements indefinitely, and the smallest particle which can take part in a chemical change is called an ‘atom’. If an atom is split as in nuclear reaction, the divided atom does not retain the original chemical properties.

Molecules. It is rare to find elements to exist naturally as single atom. Some elements have atoms which exist in pairs, each pair forming a molecule (e.g. oxygen), and the atoms of each molecule are held together by stronger inter-atomic forces. The isolation of a molecule of oxygen would be tedious, but possible; the isolation of an atom of oxygen would be a different prospect. The molecules of some substances are formed by the mating up of atoms of different elements. For example, water has a molecule which consists of two atoms of hydrogen and one atom of oxygen. The atoms of different elements have different masses and these values are important when a quantitative analysis is required. The actual masses are infinitesimally small, and the ratios of the masses of atoms are used. These ratios are indicated by atomic weight quoted on a scale which defines the atomic weight of oxygen as 16.

The symbols and molecular weights of some important elements, compounds and gases are given in Table 5.2

<table>
<thead>
<tr>
<th>Elements/Compounds/Gases</th>
<th>Molecule</th>
<th>Atom</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symbol</td>
<td>Molecular weight</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂</td>
<td>2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>16</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>28</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>12</td>
</tr>
<tr>
<td>Sulphur</td>
<td>S</td>
<td>32</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>18</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO</td>
<td>28</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>44</td>
</tr>
<tr>
<td>Sulphur dioxide</td>
<td>SO₂</td>
<td>64</td>
</tr>
<tr>
<td>Marsh gas (Methane)</td>
<td>CH₄</td>
<td>16</td>
</tr>
<tr>
<td>Ethylene</td>
<td>C₂H₄</td>
<td>28</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>30</td>
</tr>
</tbody>
</table>

5.4. COMBUSTION EQUATIONS

1. Combustion of hydrogen

Equation (1)

\[ 2H₂ + O₂ = 2H₂O \]

The above equation of combustion of hydrogen tell us that:

(i) Hydrogen reacts with water to form steam or water.
(ii) Two molecules of hydrogen react with one molecule of oxygen to give two molecules of steam or water, 

\[ 2 \text{molecules } H_2 + 1 \text{ molecule } O_2 \rightarrow 2 \text{ molecules } H_2O \]

i.e., 

\[ 2 \text{ volumes } H_2 + 1 \text{ volume } O_2 \rightarrow 2 \text{ volumes } H_2O \]

The $H_2O$ may be liquid or a vapour depending on whether the product has been cooled sufficiently to cause condensation.

The proportions by mass are obtained by using atomic weights as follows:

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

\[ . \]

\[ 2(2 \times 1) + 2 \times 16 \rightarrow 2(2 \times 1 + 16) \]

i.e., 

\[ 4 \text{ kg } H_2 + 32 \text{ kg } O_2 \rightarrow 36 \text{ kg } H_2O \]

or 

\[ 1 \text{ kg } H_2 + 8 \text{ kg } O_2 \rightarrow 9 \text{ kg } H_2O \]

Since the oxygen is accompanied by nitrogen if air is supplied for the combustion, then this nitrogen should be included in the equation. As nitrogen is inert as far as chemical reaction is concerned, it will appear on both sides of the equation. With one mole of oxygen there are $79/21$ moles of nitrogen, hence equation (1) becomes,

\[ 2H_2 + O_2 + \frac{79}{21} N_2 \rightarrow 2H_2O + \frac{79}{21} N_2 \]

\[ \text{(2)} \]

2. Combustion of carbon

(i) Complete combustion of carbon to carbon dioxide

\[ C + O_2 \rightarrow CO_2 \]

and including the nitrogen,

\[ C + O_2 + \frac{79}{21} N_2 \rightarrow CO_2 + \frac{79}{21} N_2 \]

\[ \text{(4)} \]

\[ \text{(4a)} \]

\[ \text{(4b)} \]

The volume of carbon is written as zero since the volume of solid is negligible in comparison with that of a gas.

By volume:

\[ 0 \text{ volume } C + 1 \text{ volume } O_2 + \frac{79}{21} \text{ volumes } N_2 \rightarrow 1 \text{ volume } CO_2 + \frac{79}{21} \text{ volumes } N_2 \]

By mass:

\[ 12 \text{ kg } C + (2 \times 16) \text{ kg } O_2 + \frac{79}{21} (2 \times 14) \text{ kg } N_2 \rightarrow (12 + 2 \times 16) \text{ kg } CO_2 + \frac{79}{21} (2 \times 14) \text{ kg } N_2 \]

\[ \text{i.e.,} \]

\[ 12 \text{ kg } C + 32 \text{ kg } O_2 + 105.3 \text{ kg } N_2 \rightarrow 44 \text{ kg } CO_2 + 105.3 \text{ kg } N_2 \]

\[ \text{or} \]

\[ 1 \text{ kg } C + \frac{8}{3} \text{ kg } O_2 + \frac{105.3}{12} \text{ kg } N_2 \rightarrow \frac{11}{3} \text{ kg } CO_2 + \frac{105.3}{12} \text{ kg } N_2. \]

\[ \text{(4b)} \]

(ii) The incomplete combustion of carbon. The incomplete combustion of carbon occurs when there is an insufficient supply of oxygen to burn the carbon completely to carbon dioxide.

\[ 2C + O_2 \rightarrow 2CO \]

\[ \text{(5)} \]

and including the nitrogen,

\[ 2C + O_2 + \frac{79}{21} N_2 \rightarrow 2CO + \frac{79}{21} N_2 \]

\[ \text{(6)} \]
5.5. THEORETICAL AIR AND EXCESS AIR

The minimum amount of air that supplies sufficient oxygen for the complete combustion of all the carbon, hydrogen, and any other elements in the fuel that may oxidise is called the “theoretical air”. When complete combustion is achieved with theoretical air, the products contain no oxygen.

In practice, it is found that complete combustion is not likely to be achieved unless the amount of air supplied is somewhat greater than the theoretical amount. Thus 150 per cent theoretical air means that air actually supplied is 1.5 times the theoretical air.

The complete combustion of methane with minimum amount of theoretical air and 150 percent theoretical air respectively is written as:

\[
\text{By mass:} \quad (2 \times 12) \text{ kg C} + (2 \times 16) \text{ kg O}_2 + \frac{79}{21} (2 \times 14) \text{ kg N}_2 \rightarrow 2(12 + 16) \text{ kg CO} + \frac{79}{21} (2 \times 14) \text{ kg N}_2
\]

\[
i.e., \quad 24 \text{ kg C} + 32 \text{ kg O}_2 + 105.3 \text{ kg N}_2 \rightarrow 56 \text{ kg CO} + 105.3 \text{ kg N}_2
\]

or

\[
1 \text{ kg C} + \frac{4}{3} \text{ kg O}_2 + \frac{105.3}{24} \text{ kg N}_2 \rightarrow \frac{7}{3} \text{ kg CO} + \frac{105.3}{24} \text{ kg N}_2 \quad -----(6a)
\]

If a further supply of oxygen is available then the combustion can continue

\[
2\text{CO} + \text{O}_2 + \frac{79}{21} \text{N}_2 \rightarrow 2\text{CO}_2 + \frac{79}{21} \text{N}_2 \quad -----(7)
\]

By mass:

\[
56 \text{ kg CO} + 32 \text{ kg O}_2 + \frac{79 \times 28}{21} \text{ kg N}_2 \rightarrow 88 \text{ kg CO}_2 + \frac{79 \times 28}{21} \text{ kg N}_2
\]

or

\[
1 \text{ kg CO} + \frac{4}{7} \text{ kg O}_2 + \frac{105.3}{56} \text{ kg N}_2 \rightarrow \frac{11}{7} \text{ kg CO}_2 + \frac{105.3}{56} \text{ kg N}_2 \quad -----(7a)
\]

The amount of air actually supplied may also be expressed in terms of per cent excess air. The excess air is the amount of air supplied over and above the theoretical air. Thus 150 per cent theoretical air is equivalent to 50 per cent excess air. The amount of excess air supplied varies with the type of fuel and the firing conditions. It may approach a value of 100% but modern practice is to use 25% to 50% excess air.

5.6. STOICHIOMETRIC AIR FUEL (A/F) RATIO

Stoichiometric (or chemically correct) mixture of air and fuel is one that contains just sufficient oxygen for complete combustion of the fuel.

A weak mixture is one which has an excess of air.

A rich mixture is one which has a deficiency of air.
The percentage of excess air is given as under:

\[
\text{Percentage excess air} = \frac{\text{Actual } A/F \text{ ratio} - \text{Stoichiometric } A/F \text{ ratio}}{\text{Stoichiometric } A/F \text{ ratio}} \quad \text{(10)}
\]

The ratios are expressed as follows:

For *gaseous fuels* by volume

For solid and liquid fuels by mass

For *boiler* plant the mixture is usually greater than 20% weak; for *gas turbines* it can be as much as 300% weak. *Petrol engines* have to meet various conditions of load and speed, and operate over a wide range of mixture strength. The following definition is used:

\[
\text{Mixture strength} = \frac{\text{Stoichiometric } A/F \text{ ratio}}{\text{Actual } A/F \text{ ratio}} \quad \text{(11)}
\]

The working value range between 80% (weak) and 120% (rich).

*Note.* The reciprocal of the air fuel ratio is called the *fuel-air* \((F/A)\) ratio.

### 5.7. AIR-FUEL RATIO FROM ANALYSIS OF PRODUCTS

When analysis of combustion products is known air-fuel ratio can be calculated by the following methods:

1. **Fuel composition known**
   - (i) Carbon balance method
   - (ii) Hydrogen balance method
   - (iii) Carbon-hydrogen balance method.

2. **Fuel composition unknown**
   - (i) Carbon-hydrogen balance method.

1. **Fuel composition known**
   - (i) **Carbon balance method.** When the fuel composition is known, the carbon balance method is quite accurate if combustion takes place with excess air and when free (solid) carbon is not present in the products. It may be noted that the Orsat analysis will not determine the quantity of solid carbon in the products.

   (ii) **Hydrogen balance method.** This method is used when solid carbon is suspected to be present.

   (iii) **Carbon-hydrogen balance method.** This method may be employed when there is some uncertainty about the nitrogen percentage reported by the Orsat analysis.

2. **Fuel composition unknown**

   When the fuel composition is not known the carbon-hydrogen balance method has to be employed.

### 5.8 CONVERSION OF VOLUMETRIC ANALYSIS TO WEIGHT ANALYSIS

The conversion of volumetric analysis to weight analysis involves the following steps:

1. Multiply the volume of each constituent by its molecular weight.
2. Add all these weights and then divide each weight by the total of all and express it as percentage.

### 5.9 CONVERSION WEIGHT ANALYSIS TO VOLUMETRIC ANALYSIS

1. Divide the weight of each constituent by its molecular weight.
2. Add up these volumes and divide each volume by the total of all and express it as a percentage.
5.10 WEIGHT OF CARBON IN FLUE GASES
The weight of carbon contained in one kg of flue or exhaust gas can be calculated from the amounts of CO\(_2\) and CO contained in it.

In eqn. [4 (b)], it was shown that 1 kg of carbon produces 11/3 kg of CO\(_2\) when completely burnt. Hence 1 kg of CO\(_2\) will contain 3/11 kg of carbon.

In eqn. [6 (a)], it can be seen that 1 kg of carbon produces 7/3 kg of CO, hence 1 kg CO contains 3/7 kg of carbon.

Therefore, weight of carbon per kg of fuel

\[ \frac{3}{11} \text{ CO}_2 + \frac{3}{7} \text{ CO} \]

Where CO\(_2\) and CO are the quantities of carbon dioxide and carbon monoxide present in 1 kg of flue or exhaust gas.

5.11 WEIGHT OF FLUE GASES PER KG OF FUEL BURNT
Due to supply of air, the weight of flue gas or exhaust gas is always more than that of fuel burnt. The actual weight of dry flue gases can be obtained by comparing the weight of carbon present in the flue gases with the weight of carbon in the fuel, since there is no loss of carbon during the combustion process. As the analysis of the exhaust gases is volumetric, so this must first be reduced to weight analysis.

Also, total weight of carbon in one kg of flue gas is

\[ \left( \frac{3}{11} \text{ CO}_2 + \frac{3}{7} \text{ CO} \right) \]

Therefore the weight of flue gas/kg of fuel burnt

\[ \frac{\text{Weight of carbon in one kg of fuel}}{\text{Weight of carbon in one kg of flue gas}} \]

5.12 ANALYSIS OF EXHAUST AND FLUE GAS
The most common means of analysis of the combustion products is the Orsat apparatus which is described below:

**Construction**: An Orsat’s apparatus consists of the following:
(i) A burette
(ii) A gas cleaner
(iii) Four absorption pipettes 1, 2, 3, 4.

![Fig. 5.1 Orsat apparatus](image)
**Pipette 1**: Contains ‘KOH’ (caustic soda) to absorb CO₂ (carbon dioxide)

**Pipette 2**: Contains an alkaline solution of ‘pyrogallic acid’ to absorb O₂ (oxygen)

**Pipette 3, 4**: Contain an acid solution of ‘cuprous chloride’ to absorb CO (carbon monoxide)

Furthermore the apparatus has a *levelling bottle* and a three way cock to connect the apparatus either to gases or to atmosphere.

**Procedure.** 100 cm³ of gas whose analysis is to be made is drawn into the bottle by lowering the levelling bottle. The stop cock S₄ is then opened and the whole flue gas is forced to pipette 1. The gas remains in this pipette for some time and most of the carbon dioxide is absorbed. The levelling bottle is then lowered to allow the chemical to come to its original level. The volume of gas thus absorbed is read on the scale of the measuring bottle. The flue gas is then forced through the pipette 1 for a number of times to ensure that the whole of the CO₂ is absorbed. Further, the remaining flue gas is then forced to the pipette 2 which contains pyrogallic acid to absorb whole of O₂. The reading on the measuring burette will be the sum of volume of CO₂ and O₂. The oxygen content can then be found out by subtraction. Finally, as before, the sample of gas is forced through the pipettes 3 and 4 to absorb carbon monoxide completely. The amount of nitrogen in the sample can be determined by subtracting from total volume of gas the sum of CO₂, CO and O₂ contents.

Orsat apparatus gives an analysis of the dry products of combustion. Steps may have been taken to remove the steam from the sample by condensing, but as the sample is collected over water it becomes saturated with water. The resulting analysis is nevertheless a true analysis of the dry products.

### 5.13 CALORIFIC OR HEATING VALUES OF FUELS

The “calorific value or heating value” of the fuel is defined as the energy liberated by the complete oxidation of a unit mass or volume of a fuel. It is expressed in kJ/kg for solid and liquid fuels and kJ/m³ for gases.

If a fuel contains hydrogen water will be formed as one of the products of combustion. If this water is condensed, a large amount of heat will be released than if the water exists in the vapour phase. For this reason two heating values are defined the higher or gross heating value and the lower or net heating value.

The *higher heating value*, HHV, is obtained when the water formed by combustion is completely condensed.

The *lower heating value*, LHV, is obtained when the water formed by combustion exists completely in the vapour phase.

Thus : \((HHV)_p = (LHV)_p + m \cdot h_{fg}\) \hspace{1cm} (12)

\((HHV)_v = (LHV)_v + m(u_g - u_f)\) \hspace{1cm} (13)

where \(m\) = Mass of water formed by combustion, 
\(h_{fg}\) = Enthalpy of vaporisation of water, kJ/kg,
\(u_g\) = Specific internal energy of vapour, kJ/kg, and
\(u_f\) = Specific internal energy of liquid, kJ/kg.

In almost all practical cases, the water vapour in the products is vapour, the lower value is the one which usually applies.
5.14 DETERMINATION OF CALORIFIC OR HEATING VALUES

The calorific value of fuels can be determined either from chemical analysis or in the laboratory.

Solid and Liquid Fuels

**Dulong’s formula.** Dulong suggested a formula for the calculation of the calorific value of the solid or liquid fuels from their chemical composition which is as given below.

Gross calorific value or H.H.V. =

\[
\frac{1}{100} \left[ 33800 C + 144000 \left( H - \frac{O}{8} \right) + 9270 S \right] \text{kJ/kg} \tag{14}
\]

where C, H, O and S are carbon, hydrogen, oxygen and sulphur in percentages respectively in 100 kg of fuel. In the above formula the oxygen is assumed to be in combination with hydrogen and only extra surplus hydrogen supplies the necessary heat.

**Laboratory method (Bomb calorimeter) Fig. 5.2 Bomb calorimeter**
The calorimeter is made of austenitic steel which provides considerable resistance to corrosion and enables it to withstand high pressure. In the calorimeter is a strong cylindrical bomb in which combustion occurs. The bomb has two valves at the top. One supplies oxygen to the bomb and other releases the exhaust gases. A crucible in which a weighted quantity of fuel sample is burnt is arranged between the two electrodes as shown in Fig. 5.2. The calorimeter is fitted with water jacket which surrounds the bomb. To reduce the losses due to radiation, calorimeter is further provided with a jacket of water and air. A stirrer for keeping the temperature of water uniform and a thermometer to measure the temperature up to accuracy of 0.001°C is fitted through the lid of the calorimeter.

Procedure. To start with, about 1 gm of fuel sample is accurately weighed into the crucible and a fuse wire (whose weight is known) is stretched between the electrodes. It should be ensured that wire is in close contact with the fuel. To absorb the combustion products of sulphur and nitrogen 2 ml of water is poured in the bomb. Bomb is then supplied with pure oxygen through the valve to an amount of 25 atmosphere. The bomb is then placed in the weighed quantity of water, in the calorimeter. The stirring is started after making necessary electrical connections, and when the thermometer indicates a steady temperature fuel is fired and temperature readings are recorded after 1/2 minute intervals until maximum temperature is attained. The bomb is then removed; the pressure slowly released through the exhaust valve and the contents of the bomb are carefully weighed for further analysis.

The heat released by the fuel on combustion is absorbed by the surrounding water and the calorimeter. From the above data the calorific value of the fuel can be found in the following way:

Let $w_f =$ Weight of fuel sample (kg),
$w =$ Weight of water (kg),
$C =$ Calorific value (higher) of the fuel (kJ/kg),
$w_e =$ Water equivalent of calorimeter (kg),
$t_1 =$ Initial temperature of water and calorimeter,
$t_2 =$ Final temperature of water and calorimeter,
$t_c =$ Radiation corrections, and
$c =$ Specific heat of water.

Heat released by the fuel sample = $w_f \times C$

Heat received by water and calorimeter
$= (w + w_e) \times c \times [(t_2 - t_1) + t_c].$

Heat lost = Heat gained
$w_f \times C = (w + w_e) \times c \times [(t_2 - t_1) + t_c]$

$\therefore$

$C = \frac{(w + w_e) \times c \times [(t_2 - t_1) + t_c]}{w_f}$

[Value of $c$ is 4.18 in SI units and unity in MKS units.]

Bomb calorimeter measures the higher or gross calorific value because the fuel sample is burnt at a constant volume in the bomb.

JUNKER’S GAS CALORIMETER

The calorific value of gaseous fuels can be determined by Junker’s gas calorimeter. Fig. 11.6 illustrates Junker’s gas calorimeter. Its principle is somewhat similar to Bomb calorimeter; in respect that heat
evolved by burning the gas is taken away by the water. In its simplest construction it consists of a combustion chamber in which the gas is burnt (in a gas burner). A water jacket through which a set of tubes called flues pass surrounds this chamber. Thermometers are incorporated at different places (as shown in Fig. 11.6) to measure the temperatures.

**Procedure:** A metered quantity of gas whose calorific value is to be determined is supplied to the gas burner via a gas meter which records its volume and a gas pressure regulator which measures the pressure of the gas by means of a manometer. When the gas burns the hot products of combustion travel upwards in the chamber and then downwards through the flues and finally escape to the atmosphere through the outlet. The temperature of the escaping gas is recorded by the thermometer fitted at the exit and this temperature should be as close to room temperature as possible so that entire heat of combustion is absorbed by water. The cold water enters the calorimeter near the bottom and leaves near the top. Water which is formed by condensation of steam is collected in a pot. The quantity of gas used during the experiment is accurately measured by the meter and temperature of ingoing and outgoing water is indicated by the thermometers. From the above data the calorific value of the gas can be calculated.

![Junker's Gas Calorimeter Diagram](image)
PROBLEMS

1. A coal sample gave the following analysis by weight, Carbon 85 per cent, Hydrogen 6 per cent, Oxygen 6 per cent, the remainder being incombustible. Determine minimum weight of air required per kg of coal for chemically correct composition.

   Solution.

   \[
   \begin{array}{lcr}
   \text{Element, wt. (kg)} & \text{C} = 0.85 & 0.85 \times \frac{8}{3} = 2.73 \\
   \text{H}_2 = 0.06 & 0.06 \times 8 = 0.48 \\
   \text{O}_2 = 0.06 & -
   \end{array}
   \]

   Total \( \text{O}_2 = 2.75 \) kg

   Weight of \( \text{O}_2 \) to be supplied = Wt. of \( \text{O}_2 \) needed – Wt. of \( \text{O}_2 \) already present in fuel
   = 2.75 – 0.06 = 2.69 kg

   Weight of air needed = 2.69 \times \frac{100}{23} = 11.70 \text{ kg. (Ans.)}

2. The percentage composition of sample of liquid fuel by weight is, \( \text{C} = 84.8 \) per cent, and \( \text{H}_2 = 15.2 \) per cent. Calculate (i) the weight of air needed for the combustion of 1 kg of fuel; (ii) the volumetric composition of the products of combustion if 15 per cent excess air is supplied.

   Solution.

   \[
   \begin{array}{lcr}
   \text{Element, wt. (kg)} & \text{C} = 0.848 & 0.848 \times \frac{8}{3} = 2.261 \\
   \text{H}_2 = 0.152 & 0.152 \times 8 = 1.216 \\
   \end{array}
   \]

   Total \( \text{O}_2 = 3.477 \) kg

   (i) Minimum weight of air needed for combustion
   \[
   = \frac{3.477 \times 100}{23} = 15.11 \text{ kg. (Ans.)}
   \]

   Excess air supplied
   \[
   = \frac{1511 \times 15}{100} = 2.266 \text{ kg}
   \]

   Wt. of oxygen in excess air
   \[
   = \frac{2.266 \times 23}{100} = 0.521 \text{ kg}
   \]

   Total air supplied for combustion = Minimum air + Excess air
   = 15.11 + 2.266 = 17.376 kg

   \[\text{Wt. of nitrogen (N}_2\text{) in flue gases} = \frac{17.376 \times 77}{100} = 13.38 \text{ kg.}\]
(ii) To get volumetric composition of the product of combustion let us use tabular method.

<table>
<thead>
<tr>
<th>Name of gas</th>
<th>Weight (x)</th>
<th>Molecular weight (y)</th>
<th>Proportional volume ((\frac{x}{y}))</th>
<th>Percentage volume (\frac{(\frac{x}{y})}{\Sigma(\frac{x}{y})} \times 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (_2)</td>
<td>3.109</td>
<td>44</td>
<td>0.0707</td>
<td>12.51 percent. (Ans.)</td>
</tr>
<tr>
<td>O(_2)</td>
<td>0.221</td>
<td>32</td>
<td>0.0163</td>
<td>2.80 percent. (Ans.)</td>
</tr>
<tr>
<td>N(_2)</td>
<td>13.38</td>
<td>28</td>
<td>0.4780</td>
<td>84.60 percent. (Ans.)</td>
</tr>
</tbody>
</table>

\(\Sigma x = 0.5650\)

3. Percentage volumetric analysis of a sample of flue gases of a coal fired boiler gave \(\text{CO}_2 = 10.4\); \(\text{CO} = 0.2\); \(\text{O}_2 = 7.8\) and \(\text{N}_2 = 81.6\) (by difference). Gravimetric percentage analysis of coal was \(\text{C} = 78\), \(\text{H}_2 = 6\), \(\text{O}_2 = 3\) and incombustible = 13. Estimate:

i) Weight of dry flue gases per kg of fuel

ii) Weight of excess air per kg of fuel.

**Solution.**

<table>
<thead>
<tr>
<th>Element, wt. (kg)</th>
<th>(\text{O}_2) reqd. (kg)</th>
<th>Dry products (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{C} = 0.78)</td>
<td>(0.78 \times \frac{8}{3} = 2.03)</td>
<td>(0.78 \times \frac{11}{3} = 2.86) ((\text{CO}_2))</td>
</tr>
<tr>
<td>(\text{H}_2 = 0.06)</td>
<td>(0.06 \times 8 = 0.48)</td>
<td></td>
</tr>
<tr>
<td>(\text{O}_2 = 0.03)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\text{Total }\text{O}_2 = 2.56\)

Minimum wt. of air needed for combustion = \((2.56 - 0.03) \times \frac{100}{28} = 11\) kg.

(i) Weight of dry flue gases per kg of fuel:

To determine the wt. of flue gases per kg of fuel let us use tabular method to convert volumetric analysis to analysis by weight.

<table>
<thead>
<tr>
<th>Name of gas</th>
<th>Volume per (m^3) of flue gas ((x))</th>
<th>Molecular weight ((y))</th>
<th>Relative volume (z = x \times y)</th>
<th>Weight per kg of flue gas (\frac{z}{\Sigma z})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{CO}_2)</td>
<td>0.104</td>
<td>44</td>
<td>4.576</td>
<td>0.1525</td>
</tr>
<tr>
<td>(\text{CO})</td>
<td>0.002</td>
<td>28</td>
<td>0.056</td>
<td>0.0019</td>
</tr>
<tr>
<td>(\text{N}_2)</td>
<td>0.516</td>
<td>28</td>
<td>22.848</td>
<td>0.7616</td>
</tr>
<tr>
<td>(\text{O}_2)</td>
<td>0.073</td>
<td>32</td>
<td>2.496</td>
<td>0.0832</td>
</tr>
</tbody>
</table>

\(\Sigma z = 29.976\) (say 30)

Amount of carbon present per kg of gases

\[\text{Amount of carbon present per kg of gases} = \frac{3}{11} \times 0.1525 + \frac{3}{7} \times 0.0019 = 0.0416 + 0.0003 = 0.0424 \text{ kg.}\]
Also carbon in the fuel = 0.78 kg.

\[ \text{Weight of dry flue gas per kg of fuel} = \frac{\text{Weight of carbon in 1 kg of fuel}}{\text{Weight of carbon in 1 kg of flue gas}} = \frac{0.78}{0.0424} = 18.4 \text{ kg. (Ans.)} \]

(ii) Weight of excess air per kg of fuel:

Weight of excess oxygen per kg of flue gas = 0.0332 - \(\frac{4}{7} \times 0.0019\)

\[
\begin{align*}
2\text{CO} + \text{O}_2 &= 2\text{CO}_2 \\
56 &+ 32 & = 88 \\
1\text{kg} + \frac{4}{7} \text{kg} &= \frac{11}{7} \text{kg} \\
= 0.0332 - 0.0011 \text{ (allowing for unburnt carbon monoxide)} \\
= 0.0321 \text{ kg.}
\end{align*}
\]

Weight of excess O\(_2\) per kg of fuel = 18.4 \times 0.0321 = 1.51 kg

\[ \therefore \text{Weight of excess air per kg of fuel} = \frac{1.51 \times 100}{23} = 6.56 \text{ kg. (Ans.)} \]

4. A single cylinder was supplied with a gas having the following percentage volumetric analysis; CO = 5, CO\(_2\) = 10, H\(_2\) = 50, CH\(_4\) = 25, N\(_2\) = 10. The percentage volumetric analysis of dry gases was CO\(_2\) = 8, O\(_2\) = 6 and N\(_2\) = 86. Determine the air-fuel ratio by volume.

**Solution.** Combustion equations are:

\[
\begin{align*}
\text{H}_2 + \text{O}_2 &= 2\text{H}_2\text{O} \\
1\text{vol} + 1/2\text{vol} &= 1\text{vol} \\
2\text{CO} + \text{O}_2 &= 2\text{CO}_2 \\
1\text{vol} + 1/2\text{vol} &= 1\text{vol} \\
\text{CH}_4 + 2\text{O}_2 &= \text{CO}_2 + 2\text{H}_2\text{O} \\
1\text{vol} + 2\text{vol} &= 1\text{vol} + 2\text{vol}.
\end{align*}
\]

<table>
<thead>
<tr>
<th>Gas</th>
<th>Vol (m(^3))</th>
<th>O(_2) needed (m(^3))</th>
<th>Products (m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>CO(_2)</td>
</tr>
<tr>
<td>CO</td>
<td>0.05</td>
<td>0.025</td>
<td>0.05</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>0.10</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>H(_2)</td>
<td>0.50</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>0.25</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>N(_2)</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>1.0</td>
<td>0.775</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Volume of air required = 0.775 \times 100/21 = 3.69 m\(^3\)

Volume of nitrogen in the air = 3.69 \times 79/100 = 2.92 m\(^3\)

Dry combustion products of 1 m\(^3\) of gases (V) contain 0.4 m\(^3\) of CO\(_2\) + 0.1 m\(^3\) of N\(_2\) (as given in the table) + 2.92 m\(^3\) of N\(_2\) (from air supplied for complete combustion) = 3.42 m\(^3\).
5. The following is the ultimate analysis of a sample of petrol by weight: Carbon = 85 percent; Hydrogen = 15 percent. Calculate the ratio of air to petrol consumption by weight if the volumetric analysis of the dry exhaust gas is: CO$_2$ = 11.5 percent; CO = 1.2 percent; O$_2$ = 0.9 percent; N$_2$ = 86 percent. Also find percentage excess air.

Solution.

<table>
<thead>
<tr>
<th>Name of gas</th>
<th>Volume per m$^3$ of flue gas ($x$)</th>
<th>Molecular weight ($y$)</th>
<th>Relative weight ($z = x \times y$)</th>
<th>Weight per kg of flue gas ($\frac{z}{\Sigma}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>0.115</td>
<td>44</td>
<td>5.06</td>
<td>0.1700</td>
</tr>
<tr>
<td>CO</td>
<td>0.012</td>
<td>28</td>
<td>0.336</td>
<td>0.0113</td>
</tr>
<tr>
<td>O$_2$</td>
<td>0.009</td>
<td>32</td>
<td>0.258</td>
<td>0.0096</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0.86</td>
<td>28</td>
<td>24.08</td>
<td>0.5091</td>
</tr>
<tr>
<td><strong>Σz</strong></td>
<td></td>
<td></td>
<td><strong>Σ = 29.76</strong></td>
<td><strong>Σ = 29.76</strong></td>
</tr>
</tbody>
</table>

:\. Weight of carbon per kg of flue gas

\[ \text{Weight of carbon per kg of flue gas} = \frac{0.0113 \times 0.17 + 0.0113 \times 0.0113}{0.5091} = 0.0512 \text{ kg} \]

\:. Weight of dry flue gas per kg of fuel

\[ \text{Weight of dry flue gas per kg of fuel} = \frac{0.85}{0.0512} = 16.6 \text{ kg} \]

\:. Vapour of combustion

\[ \text{Vapour of combustion} = 6 \times 0.15 = 1.35 \text{ kg} \]

\:. Total weight of gas

\[ \text{Total weight of gas} = 16.6 + 1.35 = 17.95 \text{ kg per kg of fuel} \]

\:. Air supplied

\[ \text{Air supplied} = (17.95 - 1) = 16.95 \text{ kg/kg of fuel} \]

\:. Ratio of air to petrol

\[ \text{Ratio of air to petrol} = 16.95 : 1. \text{ (Ans.)} \]

\:. Stoichiometric air

\[ \text{Stoichiometric air} = \left[ \frac{0.85 \times \frac{8}{3} + (0.15 \times 8)}{23} \times \frac{100}{23} \right] \]

\[ = 16.07 \text{ kg per kg of fuel} \]

\:. Excess air

\[ \text{Excess air} = 16.95 - 16.07 = 1.88 \text{ kg} \]

\:. Percentage excess air

\[ \text{Percentage excess air} = \frac{1.88}{16.07} \times 100 = 12.47\% \text{. (Ans.)} \]
6. A sample of fuel has the following percentage composition: Carbon = 86 per cent; Hydrogen = 8 per cent; Sulphur = 3 per cent; Oxygen = 2 per cent; Ash = 1 per cent. For an air-fuel ratio of 12 : 1, calculate: (i) Mixture strength as a percentage rich or weak. (ii) Volumetric analysis of the dry products of combustion.

**Solution.**

<table>
<thead>
<tr>
<th>Element, wt. (kg)</th>
<th>$O_2$ reqd. (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C = 0.86</td>
<td>$0.86 \times \frac{8}{3} = 2.29$</td>
</tr>
<tr>
<td>$H_2 = 0.08$</td>
<td>$0.08 \times 8 = 0.64$</td>
</tr>
<tr>
<td>S = 0.03</td>
<td>$0.03 \times \frac{1}{3} = 0.03$</td>
</tr>
<tr>
<td>$O_2 = 0.02$</td>
<td>Total $O_2 = 2.96$</td>
</tr>
</tbody>
</table>

Weight of oxygen to be supplied per kg of fuel = $2.96 - 0.02 = 2.94$ kg

Weight of minimum air required for complete combustion = $\frac{2.94 \times 100}{23} = 12.78$ kg

Hence “correct” fuel-air ratio = $\frac{1}{12.78} : 1$

But actual ratio is $\frac{1}{12} : 1$.

(i) **Mixture strength** = $\frac{12.78}{12} \times 100 = 106.5\%$

This show that mixture is 6.5% rich. (Ans.)

Deficient amount of air = $12.78 - 12 = 0.78$ kg

Amount of air saved by burning 1 kg of C to CO instead of CO$_2$

= Oxygen saved $\times \frac{100}{23}$

= $\left[ \frac{8}{3} (CO_2) - \frac{4}{3} (CO) \right] \times \frac{100}{23} = 5.8$ kg

Hence $\frac{0.78}{5.8} = 0.134$ kg of carbon burns to CO and as such $0.86 - 0.134 = 0.726$ kg of carbon burns to CO$_2$.

\[ \therefore \quad \text{CO formed} \quad = 0.134 \times \frac{7}{3} = 0.313 \text{ kg} \]

\[ \text{CO}_2 \text{ formed} \quad = 0.726 \times \frac{11}{3} = 2.662 \text{ kg} \]

\[ \text{N}_2 \text{ supplied} \quad = 12 \times 0.77 = 9.24 \text{ kg} \]

\[ \text{SO}_2 \text{ formed} \quad = 0.03 \times 2 = 0.06 \text{ kg} \]
(ii) **The percentage composition of dry flue gases** is given as below:

<table>
<thead>
<tr>
<th>Dry products</th>
<th>Weight (kg)</th>
<th>Molecular weight</th>
<th>Proportional volume ( z = \frac{x}{y} )</th>
<th>Percentage volume ( \frac{z}{\Sigma z} \times 100 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.313</td>
<td>28</td>
<td>0.0112</td>
<td>2.78 per cent (Ans.)</td>
</tr>
<tr>
<td>( \text{CO}_2 )</td>
<td>2.062</td>
<td>44</td>
<td>0.0505</td>
<td>15.63 per cent (Ans.)</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>9.24</td>
<td>28</td>
<td>0.3300</td>
<td>81.97 per cent (Ans.)</td>
</tr>
<tr>
<td>( \text{SO}_3 )</td>
<td>0.06</td>
<td>64</td>
<td>0.0009</td>
<td>0.22 per cent (Ans.)</td>
</tr>
</tbody>
</table>

\( \Sigma z = 0.4029 \)