7.1 Introduction

Combustion or burning is a chemical process in which the inflammable matter in a substance combines with oxygen at a temperature above the ignition temperature of the substance and results in the evolution of heat and light. A fuel, at the time of burning, must be in gaseous forms so as to unite with oxygen, which is present in the air. A liquid fuel has to be vaporised or atomised before it is burnt. The process of gasifying a solid fuel and mixing it with the air at the proper temperature is more difficult and many means have been adopted in recent years to accomplish the proper burning of solid fuels.

The combustion process involves the oxidation of constituents in the fuel that are capable of being oxidized, and can, therefore, be represented by a chemical equation. These equations indicate how much oxygen is required to combine with the given amount of fuel and also the amount of resulting gases produced by the combustion. The knowledge of these tests enables an engineer to determine the correct amount of air to be supplied and the amount of the heat carried away by the products of combustion up the chimney.

To accomplish perfect combustion, there should be an ample supply of air, a thorough mixing of the air, and a sufficiently high temperature to maintain combustion.

7.2 Chemistry of Combustion

Fuels are made up of substances such as carbon and hydrogen with small amount of oxygen, nitrogen, sulphur, etc. These substances are basic elements which cannot be broken down into simpler parts having different properties. However, if temperature and pressure conditions are favourable, these elements may combine and produce an entirely different substance. This substance is known as chemical compound. For example, when carbon combines with oxygen, the compound formed is carbon dioxide. Again, if hydrogen combines with oxygen, the compound formed is water.

All substances are composed of minute particles of chemical elements. These minute particles are called atoms and these atoms are arranged in groups, called molecules. The elements can be represented, for convenience, by symbols. The symbols C, H, O, and S represent one atom each of carbon, hydrogen, oxygen and sulphur respectively.

Hydrogen is used as the standard gas in order to introduce quantity in combustion calculations. The volume of one kg of hydrogen at 0°C and 760 mm of Hg pressure is 11.2 m³ and this is taken as the standard volume.

The mass of one standard volume of any element under the above condition of pressure and temperature and in the form of a gas, is the atomic weight of the element.
The molecular weight of a substance is the mass of two standard volumes (22.4 m³) of that substance when in the form of a gas at normal temperature and pressure. Both elements and compounds have molecular weights. The atomic weights are purely relative and are arbitrarily established. Hydrogen which is the lightest known element has been given the atomic weight 1 (one) and the weights of other elements are fixed in relation to it.

7.3 Mol and Molar Volume

When dealing with mixture of gases and gas reactions, it is more convenient to use the molecular weight of the gases as unit of mass and not the kilogram. Although the values in table 7-1 is not the true mass of a molecule in kilogram, they may be considered, for convenience, as mass in kilogram. The mass of a substance in kilogram equal to its tabulated molecular weight is called a kg-mol or kilogram-mol. Thus, one kg-mol of hydrogen means 2 kg of hydrogen, and one kg-mol of oxygen means 32 kg of oxygen.

The corresponding volume of the gas of this unit (kg-mol) at 0°C and 760 mm Hg is known as the molar volume. For example, the molar volume of hydrogen is 22.4 m³ which is the volume of 2 kg of hydrogen at 0°C and 760 mm Hg.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Atomic symbol</th>
<th>Atomic weight</th>
<th>Molecular symbol</th>
<th>Molecular weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>1</td>
<td>H₂</td>
<td>2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>16</td>
<td>O₂</td>
<td>32</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
<td>14</td>
<td>N₂</td>
<td>28</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>12</td>
<td>C</td>
<td>12</td>
</tr>
<tr>
<td>Sulphur</td>
<td>S</td>
<td>32</td>
<td>S</td>
<td>32</td>
</tr>
<tr>
<td>Water or Steam</td>
<td></td>
<td></td>
<td>H₂O</td>
<td>18</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td></td>
<td></td>
<td>CO₂</td>
<td>44</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td></td>
<td></td>
<td>CO</td>
<td>28</td>
</tr>
<tr>
<td>Sulphuric dioxide</td>
<td></td>
<td></td>
<td>SO₂</td>
<td>64</td>
</tr>
<tr>
<td>Methane</td>
<td></td>
<td></td>
<td>CH₄</td>
<td>16</td>
</tr>
<tr>
<td>Ethylene or Olefiant gas</td>
<td></td>
<td></td>
<td>C₂H₄</td>
<td>28</td>
</tr>
<tr>
<td>Acetylene</td>
<td></td>
<td></td>
<td>C₂H₂</td>
<td>26</td>
</tr>
</tbody>
</table>

When the substance (compounds) are made up of different elements, their molecular weight can be calculated by adding the atomic weight of elements concerned. For example one molecule of steam (H₂O) consists of 2 atoms of hydrogen + 1 atom of oxygen.

\[
\text{Molecular weight of } \text{H}_2\text{O} = (1 \times 2) + 16 = 18
\]

Similarly, 1 molecule of CO₂ consists of 1 atom of carbon + 2 atoms of oxygen.

\[
\text{Molecular weight of } \text{CO}_2 = 12 + (2 \times 16) = 44
\]

The table 7-1 gives the atomic weights of elements, and molecular weights of gaseous elements and chemical compounds which are frequently used in combustion calculations.

The molar volume is constant for all gases when they are at the same pressure and temperature. This is according to Avogadro's law which states that the equal volumes of different gases at the same temperature and pressure contain equal number of
molecules. The numerical value of the molar volume of all gases at a temperature of
0°C and 760 mm Hg is 22.4 cubic metres. In other words, under these specified
conditions, 22.4 m³ of hydrogen weighs 2 kg, whilst the same volume (22.4 m³) of
oxygen weighs 32 kg, and so on.

7.4 Chemical Reactions

The chemical union of substances may be expressed by an equation or reaction,
as it is called, Chemical equations are very valuable to engineers because they also
indicate the proportions with which the elements react when there is to be no surplus.
The union of hydrogen with oxygen produces steam. Symbolically this reaction is written as

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

The positive sign indicates that a chemical reaction has taken place. The sign has
no algebraic interpretation. The equation reads that one kg of hydrogen unites with 8
kg of oxygen to produce 9 kg of steam or 2 kg-moles of hydrogen combine with 1
kg-mol of oxygen to form 2 kg-moles of steam.

All the initial substances that undergo the combustion process are called the
reactants, and the substances that result from the combustion process are called
products. From this example, it should be understood that a chemical equation not
only expresses the result of reactions but it also has a quantitative significance. The
equation obeys mathematical laws as the total mass on either side of the equation is
the same.

Since it is difficult to measure the mass of gas directly, it is more usual to consider
the volumes which unite instead of the masses. Take for example, the chemical equation,

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

This equation can be read as "two cubic metres of H₂ combine with one cubic
metre of O₂ to produce two cubic metres of steam at the same state as that of H₂
and O₂", provided the steam produced obeys the laws of perfect gases.

At high temperatures steam obeys the laws of perfect gases but at low temperatures
steam would condense and its volume then would be negligible in comparison with that
of the gases. A similar situation arises with the solid carbon in the equation C + O₂
= CO₂, which should not be read as one cubic metre of carbon combines with one
cubic metre of oxygen because the volume of oxygen uniting with carbon is so great
that the volume of carbon becomes negligible in comparison. It may, therefore, be said
that one cubic metre of O₂ after reacting with C, produces one cubic metre of CO₂
at the same pressure and temperature as that of O₂.

The following chemical equations represent the combustion of different constituents
of a fuel and they are most frequently used in combustion calculations:

Burning of Carbon to Carbon dioxide (complete combustion)

\[ C + O_2 \rightarrow CO_2 \]

\[ 12 + 16 \times 2 = 12 + 16 \times 2 \]

i.e. \[ 12 + 32 = 44 \]
or \[ 1 + 2.67 = 3.67 \]
i.e. 1 kg of Carbon needs 2.67 kg of Oxygen and produces 3.67 kg of Carbon dioxide.

Burning of Carbon to Carbon monoxide (incomplete combustion)
\[ 2C + O_2 = 2CO \]
\[ 2(12) + 16 = 2(12 + 16) \]
i.e. \[ 24 + 32 = 56 \]
or \[ 1 + 1.33 = 2.33 \]
i.e. 1 kg of C takes 1.33 kg of O_2 and produces 2.33 kg of CO.

Burning of Sulphur to Sulphur dioxide
\[ S + O_2 = SO_2 \]
\[ 32 + 16 = 32 + 16 \]
i.e. \[ 1 + 1 = 2 \]
i.e. 1 kg of S needs 1 kg of O_2 and produces 2 kg of SO_2.

Burning of Hydrogen to Steam
\[ 2H + O_2 = 2H_2O \]
\[ 2(1) + 16 = 2(1 + 16) \]
i.e. \[ 1 + 8 = 9 \]
i.e. 1 kg of Hydrogen needs 8 kg of O_2 and produces 9 kg of steam.

Burning of Carbon monoxide to Carbon dioxide
\[ 2CO + O_2 = 2CO_2 \]
i.e. \[ 2(12 + 16) + 2 = 2(12 + 16 + 2) \]
i.e. \[ 1 + \frac{4}{7} = \frac{1}{7} \]
i.e. 1 kg of CO needs 4/7 kg of O_2 and produces 11/7 kg of CO_2.

Methane
\[ CH_4 + 2O_2 = CO_2 + 2H_2O \]
i.e. \[ (12 + 1 \times 4) + 2(16 \times 2) = (12 + 16 \times 2) + 2(1 \times 2 + 16) \]
or \[ 1 + 4 = \frac{11}{4} + \frac{9}{4} \]

Ethylene
\[ C_2H_4 + 3O_2 = 2CO_2 + 2H_2O \]
i.e. \[ (12 \times 2 + 1 \times 4) + 3(16 \times 2) = 2(12 + 16 \times 2) + 2(1 \times 2 + 16) \]
or \[ 1 + 3.43 = 3.14 + 1.29 \]

Acetylene
\[ 2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O \]
i.e. \[ 2(12 \times 2 + 1 \times 2) + 5(16 \times 2) = 4(12 + 2 \times 16) + 2(1 \times 2 + 16) \]
or \[ 1 + 3.08 = 3.39 + 0.69 \]
From the point of view of combustion it is usual to assume that air is a mixture of oxygen and nitrogen, their proportions being:

On mass basis, oxygen 23 per cent, nitrogen 77 per cent, and
By volume, oxygen 21 per cent, nitrogen 79 per cent.

This means that one kg of oxygen is associated with $\frac{77}{23} = 3.35$ kg of nitrogen in $(1 + 3.35) = 4.35$ kg of air. Also, one cubic metre of oxygen is associated with $\frac{79}{21} = 3.76$ m$^3$ of nitrogen in $(1 + 3.76) = 4.76$ m$^3$ of air.

The nitrogen is an inert gas and takes no part in the chemical reaction occurring. Its presence in the air lowers the temperature of combustion, retards the intimate mixing of the fuel with oxygen, and also carries away heat up the chimney of the boiler.

The knowledge of the chemical composition of the fuel to be burnt and the application of chemistry to combustion problems enables the determination of the theoretical or minimum amount of the air required to burn completely a solid fuel or a liquid fuel or a gaseous fuel.

Once the mass of theoretical air required is determined, the actual air supplied can be adjusted to avoid undue heat losses. In practice, the quantity of air in excess of the theoretical air must be supplied to ensure complete combustion as some of the air may pass off without any chemical reaction. This extra amount of air supplied, is known as excess air and varies with the type and quantity of the fuel used, and the method of firing. In practice, excess air to the extent of 30% to 50% of the theoretical or minimum air is supplied to burn the fuel completely.

It should be noted that too great an excess air results in:

- lowering furnace temperature,
- increased heat loss in the chimney gases,
- increased smoke, and
- more power required to handle air and flue gases to produce artificial draught.

Too small an excess air results in:
- increasing furnace temperature, which may have bad effects on the structures and components of furnace, and
- incomplete combustion.

7.5 Combustion Problems

In the problems of combustion of fuels, the values of the following items are usually required to be determined by calculations:

- Mass and volume of minimum or theoretical air required for the complete combustion of 1 kg of fuel,
- Conversion of volumetric composition of a gas to composition on mass basis.
- Conversion of composition of a gas on mass basis to composition by volume.
- Mass of carbon in one kg of flue gases,
- Mass of flue gases produced per kg of fuel burned,
- Mass of total or actual air, and excess air supplied per kg of fuel,
- Flue gas analysis by volume and on mass basis.
Heat carried away by flue gases per kg of fuel, and

Volume of minimum air required for complete combustion of one m³ of gaseous fuel.

The products of combustion that pass away through the combustion chamber to
the chimney are called flue gases. The products of combustion from a fuel containing
H, C, and S are: water vapour, CO₂, and/or CO and SO₂. These products form part
of the flue gases from the combustion chamber. Other components of flue gases present
are nitrogen and excess oxygen supplied with excess air. The nitrogen is from the air
supplied for combustion purpose, and it may also originally be present in fuel.

The CO₂, CO, SO₂ and N₂ are called dry flue gases or products of combustion
and the volumetric percentage of these gases can be determined by means of the
Orsat apparatus described later.

7.6 Theoretical or Minimum Air Required for Combustion

It will be seen from the chemical equations in Art. 7.4 that for combustion,
Carbon requires 2.67 times its own mass of oxygen,
Hydrogen requires 8 times its own mass of oxygen, and
Sulphur requires its own mass of oxygen.

Considering 1 kg of a fuel, whose ultimate analysis gives Carbon, C kg; Hydrogen,
H kg; Oxygen, O kg; and Sulphur, S kg (remainder being incombustible), then
Oxygen required to burn C kg of carbon = 2.67 C kg.
Oxygen required to burn H kg of hydrogen = 8 H kg.
Oxygen required to burn S kg of sulphur = S kg.

Total oxygen required for complete combustion of 1 kg of fuel = (2.67 C + 8 H + S) kg.

As the fuel already contains O kg of oxygen which we assume can be used for
combustion,

Theoretical oxygen required for complete combustion of 1 kg of fuel
= (2.67 C + 8 H + S - O) kg.

Since, the air contains 23% of oxygen on mass basis (the remaining 77% being
considered as nitrogen),

1 kg of oxygen is contained in 100/23 kg of air.

Hence, minimum or theoretical mass of air required for complete combustion of
1 kg of fuel = 100/23 (2.67 C + 8 H + S - O) kg

Problem-1: Percentage composition of fuel on mass basis is C, 87.1%; H₂ 4.4%; O₂,
1.2%; and ash, 7.3. Find the minimum or theoretical mass and volume of air required
to burn 1 kg of the fuel.

The oxygen required to burn the two combustibles (carbon and hydrogen) may first
be found. The chemical reactions are:

(i) C + O₂ = CO₂ (ii) 2H₂ + O₂ = 2H₂O
12 + 32 = 44 4 + 32 = 36
or 1 + 2.67 = 3.67 or 1 + 8 = 9

The equations show that 1 kg of C requires 2.67 of O₂ to burn it, and
1 kg of $H_2$ requires 8 kg of $O_2$ to burn it.

Mass of $C$ in 1 kg of fuel = 0.871 kg (by given composition).

$\therefore O_2$ required to burn 0.871 kg of $C = 0.871 \times 2.67 = 2.323$ kg.

Mass of $H_2$ in 1 kg of fuel = 0.044 (by given composition).

$\therefore O_2$ required to burn 0.044 kg of $H_2 = 0.044 \times 8 = 0.352$ kg.

$\therefore$ Total $O_2$ required = 2.323 + 0.352 = 2.675 kg/kg of fuel.

But, 0.012 of $O_2$ is already present in 1 kg of fuel (by given composition).

$\therefore$ Net $O_2$ required to burn 1 kg of fuel = 2.675 - 0.012 = 2.663 kg

As oxygen present in 100 kg of air is 23 kg,

Minimum mass of air required to burn 1 kg of fuel completely

$= 2.663 \times 100/23 = 11.66$ kg.

Alternatively, using eqn. (7.1), minimum mass of air required for complete combustion of one kg of fuel

$= \frac{100}{23} [2.67C + 8H + S - O]$

$= \frac{100}{23} [(2.67 \times 0.871) + (8 \times 0.044) - 0.012] = 11.66$ kg per kg of fuel (same as before).

To find theoretical or minimum volume of air required:

The density of gas is proportional to its molecular weight and inversely to its molar volume. The molar volume of a gas at 0°C and 760 mm Hg (N.T.P.) is 22.4 m$^3$.

$\therefore$ Density of $O_2$ at 0°C and 760 mm Hg = $\frac{\text{molecular weight}}{\text{molar volume}} = \frac{32}{22.4} = 1.429$ kg/m$^3$

Hence, volume of $O_2$ required = $\frac{\text{mass of } O_2}{\text{density}} = \frac{2.663}{1.429} = 1.843$ m$^3$

As $O_2$ is 21 per cent by volume in air, minimum volume of air required for complete combustion of 1 kg of fuel = $1.843 \times \frac{100}{21} = 8.776$ m$^3$ per kg of fuel.

Problem-2: A sample of fuel was found to have the following percentage composition on mass basis: $C$, 80; $H_2$, 16; and ash etc., 4. Determine the minimum or theoretical mass and volume of air required to burn 1 kg of this fuel.

Chemical reactions are:

(1) $C + O_2 = CO_2$

(2) $2H_2 + O_2 = 2H_2O$

$12 + 32 = 44$

$4 + 32 = 36$

$1 + 2.67 = 3.67$

$1 + 8 = 9$

$\therefore O_2$ required to burn 0.8 kg of carbon = $0.8 \times 2.67 = 2.13$ kg

$\therefore O_2$ required to burn 0.16 kg of hydrogen = $0.16 \times 8 = 1.28$ kg

$\therefore$ Total $O_2$ required = 2.13 + 1.28 = 3.41 kg/kg of fuel

$\therefore$ Minimum mass of air required to burn one kg of fuel

$= 3.41 \times 100/23 = 14.83$ kg/kg of fuel.
Alternatively, using eqn. (7.1), minimum mass of air required for complete combustion of one kg of fuel = \[
\frac{100}{23} \left[ 2.67C + 8H + S - O \right] = \frac{100}{23} \left[ (2.67 \times 0.8) + (8 \times 0.16) \right] = 14.83
\]
kg/kg of fuel (same as before)

Density of O\textsubscript{2} at N.T.P. \[
\frac{\text{molecular weight}}{\text{molar volume}} = \frac{32}{22.4} = 1.429 \text{ kg/m}^3
\]

Hence, volume O\textsubscript{2} required to burn 1 kg of fuel = \[
\frac{3.41}{1.429} = 2.387 \text{ m}^3
\]

\[\therefore\] Minimum volume of air required = \[
2.387 \times 100/21 = 11.366 \text{ m}^3/\text{kg of fuel}
\]

7.7 Conversion of Volumetric Composition on Mass Basis

Following example illustrates the procedure to convert the given volumetric composition of gas on mass basis.

Problem-3: The volumetric analysis of a fuel gas is: CO\textsubscript{2}, 15%; CO, 2.2%; O\textsubscript{2}, 1.6%; N\textsubscript{2}, 81.2%. Convert this volumetric composition to percentage composition on mass basis.

To convert volume of CO\textsubscript{2} to mass of CO\textsubscript{2}:

Let \(v\) be the volume of CO\textsubscript{2} in m\textsuperscript{3} at the existing pressure and temperature of the flue gas whose analysis is given above. The volumes of the other constituents CO, O\textsubscript{2} and N\textsubscript{2} will also be \(v\), since they are all at the same temperature and pressure. It is not necessary to know the exact value of this volume \(v\), since it will ultimately be cancelled on division. The volume of CO\textsubscript{2} per cubic metre of flue gas is 0.15 m\textsuperscript{3}. Since, the mass of \(v\) m\textsuperscript{3} volume of CO\textsubscript{2} is proportional to 44 (its molecular weight),

The proportional mass of 0.15 m\textsuperscript{3} of CO\textsubscript{2} = \[
\frac{44}{v} \times 0.15 = \frac{6.6}{v} \text{ kg.}
\]

The proportional mass of CO, O\textsubscript{2} and N\textsubscript{2} may similarly be calculated and tabulated as shown in the table. The sum of all these proportional masses may then be found and it is \(\frac{30.477}{v}\) in this case. In \(\frac{30.477}{v}\) kg of flue gas, the mass of CO\textsubscript{2} is \(\frac{6.6}{v}\) kg.

\[\therefore\] Mass of CO\textsubscript{2} in 1 kg of flue gas = \[
\frac{6.6}{v} \times \frac{v}{30.477} = 0.216 \text{ kg i.e. 21.6%}
\]

The mass of other products per kg of flue gas and their percentages on mass basis can be calculated in the same manner and tabulated as shown below. The process of conversion of volumetric analysis to analysis on mass basis is simplified by constructing a table as under:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Volume in one m\textsuperscript{3} of \textit{flue gas} (a)</th>
<th>Molecular weight (b)</th>
<th>Proportional mass in kg (c) = (a) x (b)</th>
<th>Mass per kg of flue gas (d) = (c) / (\sum) (c)</th>
<th>Percentage mass (e)</th>
</tr>
</thead>
</table>
| CO\textsubscript{2} | 0.150 | 44 | \[
\frac{44}{v} \times 0.15 = \frac{6.6}{v} \text{ kg}.
\] | \[
\frac{6.6}{30.477} = 0.216
\] | 21.6 |
| CO | 0.022 | 28 | \[
\frac{28}{v} \times 0.022 = \frac{0.615}{v} \text{ kg}
\] | \[
\frac{0.615}{30.477} = 0.022
\] | 2.2 |
| O\textsubscript{2} | 0.016 | 32 | \[
\frac{32}{v} \times 0.016 = \frac{0.512}{v} \text{ kg}
\] | \[
\frac{0.512}{30.477} = 0.017
\] | 1.7 |
| N\textsubscript{2} | 0.812 | 28 | \[
\frac{28}{v} \times 0.812 = \frac{22.75}{v} \text{ kg}
\] | \[
\frac{22.75}{30.477} = 0.745
\] | 74.5 |
| Total | = 1.000 | - | \[
\frac{30.477}{v}
\] | \[
\frac{1}{1} = 1.000
\] | 100.00 |
— In short, the above procedure can be summarised as follows:
— Multiply volume of each constituent in one m$^3$ of flue gas, by its molecular weight.
— Find the sum of the products and divide each constituent by this sum.
— The result is the mass of each constituent in 1 kg of the flue gas.
— To have its percentage mass, multiply this mass by 100.

7.8 Conversion of Composition on Mass Basis to Composition by Volume

In order to convert analysis on mass basis to volume basis,
— Divide mass of each constituent in one kg of flue gas by its molecular weight.
— Find the sum of the quotients, and divide each quotient by this sum.
— The result is the volume of each constituent in one m$^3$ of flue gas.
— For percentage volume multiply this volume by 100.

This is reverse of the procedure just described for the conversion of volumetric analysis to analysis on mass basis.

Problem-4: The percentage composition of the flue gas on mass basis: CO$_2$, 16; CO, 1; O$_2$, 7; and N$_2$, 76. Convert this analysis on mass basis to percentage volumetric analysis.

The process of conversion of analysis on mass basis to volumetric analysis is simplified by constructing the table as under:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>% mass analysis in kg (a)</th>
<th>Molecular weight (b)</th>
<th>Relative volume (c) = (a) / (b)</th>
<th>Percentage volumetric analysis (d) = (c) / Σ(c) x 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>16</td>
<td>44</td>
<td>$\frac{16}{44} = 0.3640$</td>
<td>$\frac{0.3640}{3.3382} \times 100 = 10.90$</td>
</tr>
<tr>
<td>CO</td>
<td>1</td>
<td>28</td>
<td>$\frac{1}{28} = 0.0357$</td>
<td>$\frac{0.0357}{3.3382} \times 100 = 1.05$</td>
</tr>
<tr>
<td>O$_2$</td>
<td>7</td>
<td>32</td>
<td>$\frac{7}{32} = 0.2185$</td>
<td>$\frac{0.2185}{3.3382} \times 100 = 6.55$</td>
</tr>
<tr>
<td>N$_2$</td>
<td>76</td>
<td>28</td>
<td>$\frac{76}{28} = 2.7200$</td>
<td>$\frac{2.7200}{3.3382} \times 100 = 81.50$</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td></td>
<td>$\Sigma(c) = 3.3382$</td>
<td>$100.00$</td>
</tr>
</tbody>
</table>

7.9 Mass of Carbon in Unit Mass of Flue Gases

Following example illustrates the method of estimation of mass of carbon in one kg of flue gases, if the volumetric analysis of flue gases is available.

Problem-5: Volumetric analysis of flue gas is CO$_2$, 15%; CO, 2.2%; O$_2$, 1.6%; and N$_2$, 81.2%. Find the mass of carbon in one kg of this flue gas.

The data is the same as that considered in problem 3. The conversion of the volumetric analysis of CO$_2$ and CO into the mass has been done in problem 3 and the mass of CO$_2$ and CO were found to be 0.216 kg and 0.022 kg respectively. The carbon is contained only in CO$_2$ and CO. Equations for reactions are:

(i) $C + CO_2 = CO_2$
(ii) $2C + O_2 = 2CO$

$12 + 32 = 44$
$24 + 32 = 56$

Mass of carbon in 0.216 kg of CO$_2$ = $\frac{12}{44} \times 0.216 = 0.059$ kg
Mass of carbon in 0.022 kg of CO = 24/56 \times 0.022 = 0.00943 kg

\therefore \text{Total mass of carbon} = 0.059 + 0.00943 = 0.06843 \text{ kg/kg of flue gas.}

7.10 Mass of Flue Gases produced per Unit Mass of Fuel

Problem-6: The percentage composition of a certain fuel on mass basis is: C, 87.1; H\textsubscript{2}, 4.4; O\textsubscript{2}, 1.2; and ash, 7.3. The volumetric composition of dry flue gas is: CO\textsubscript{2}, 15%; CO, 22%; O\textsubscript{2}, 1.6%; and N\textsubscript{2}, 81.2%. Find the mass of flue gases produced per kg of fuel burned.

It may be noted that there is no loss of carbon during the process of combustion. The mass of carbon in the products must be the same if the combustion is complete.

The volumetric composition of dry flue gas is same as considered in problem 5. The total mass of carbon in 1 kg of the flue gas is found to be 0.06843 kg. The mass of carbon in 1 kg of fuel in this problem is 0.871 kg (87.1% as per composition of the fuel.)

Since, 0.06843 kg of carbon is contained in 1 kg of flue gas, 0.871 kg of carbon will be contained in \( \frac{0.871}{0.06843} = 12.8 \) kg of flue gas.

Thus, mass of flue gas produced per kg of fuel burnt is 12.8 kg.

7.11 Mass of Actual and Excess Air Supplied per Unit Mass of Fuel

The procedure of estimation of actual air and excess air supplied per kg of fuel when fuel and flue gas analysis is available, is outlined in the following problem.

Problem-7: The following is a percentage analysis by volume of dry flue gas:

\[ \text{CO}_2 = 11.9; \text{CO} = 0.1; \text{O}_2 = 6.2; \text{and N}_2 = 81.8. \]

Calculate the actual air drawn through the furnace per kg of coal fired and the excess air supplied per kg of coal fired assuming that the coal contains 86.8% of carbon.

Relative composition on mass basis of the flue gas
\[ \text{CO}_2, 11.9 \times 44; \text{CO}, 0.1 \times 28; \text{O}_2, 6.2 \times 32; \text{and N}_2, 81.8 \times 28. \]

\[ \therefore 11.9 \times 44 \text{ kg CO}_2 \text{ requires } 11.9 \times 44 \times \frac{12}{44} \text{ kg carbon for formation,} \]

and \[ 0.1 \times 28 \text{ kg CO requires } 0.1 \times 28 \times \frac{12}{28} \text{ kg carbon for formation.} \]

Total amount of carbon in flue gases = 11.9 \times 12 + 0.1 \times 12 = 144 kg.

\[ \therefore \text{Ratio of relative mass of nitrogen to carbon in flue gases} = \frac{81.8 \times 28}{144} \]

But, as each kg of coal contains 0.868 kg of carbon,

Mass of nitrogen per kg of coal = \( \frac{81.8 \times 28}{144} \times 0.868 = 13.775 \) kg.

Air contains 77% nitrogen by weight.

\[ \therefore \text{Actual air required (supplied) per kg of coal fired} = 13.775 \times \frac{100}{77} = 17.9 \text{ kg.} \]

Alternative method of determining actual air supplied (approximate):

Actual air required (supplied) per kg of coal = \( \frac{N \times C}{33(C_1 + C_2)} \)}
where \( N, C_1 \) and \( C_2 \) are percentages of nitrogen, carbon dioxide and carbon monoxide by volume in flue gases, and \( C \) is the percentage of carbon in fuel on mass basis.

Actual air supplied per kg of coal fired = \( \frac{81.8 \times 86.8}{33 (11.9 + 0.1)} \) = 17.9 kg (same as before)

**Excess air**

Oxygen in the flue gases is 6.2% by volume. This oxygen is the oxygen of the excess air.

The amount of nitrogen associated with this oxygen = \( 6.2 \times \frac{79}{21} = 23.32 \)

and the ratio of the excess air to the total air supplied = \( \frac{23.32}{81.8} \)

\( \therefore \) Mass of excess air supplied per kg of coal fired = \( \frac{23.32}{81.8} \times 17.9 = 5.1 \) kg.

**Alternative method of determining excess air (approximate)**

Mass of excess air supplied per kg of coal = \( \frac{79 \times O \times C}{21 \times 33 (C_1 + C_2)} \)

where \( C_1, C_2 \) and \( O \) are percentages of carbon dioxide, carbon monoxide and oxygen by volume in flue gases, and \( C \) is the percentage of carbon in fuel on mass basis.

\( \therefore \) Mass of excess air supplied per kg of coal fired.

\( = \frac{79 \times 6.2 \times 86.8}{21 \times 33 (11.9 + 0.1)} = 5.1 \) kg (same as before)

**Problem 8**

During a boiler trial, the dry flue gas analysis by volume was reported as: CO\(_2\), 13%; CO, 0.3%; O\(_2\), 6%; and N\(_2\), 80.7%. The coal analysis on mass basis was reported as: C, 62.4%; H\(_2\), 4.2%; O\(_2\), 4.5%; moisture, 15%; and ash, 13.9%.

Calculate: (i) the theoretical air or minimum air required to burn 1 kg of coal (ii) the mass of air actually supplied per kg of coal, and (iii) the amount of excess air supplied per kg of coal burnt. (Air contains 23% oxygen on mass basis).

(i) Oxygen required to burn carbon and hydrogen may first be found.

The chemical reactions are:

(i) \( C + O_2 \rightarrow CO_2 \)

\( 12 + 16 \times 2 = 12 + 16 \times 2 \)

\( i.e. \ 12 + 32 = 44 \)

or 1 kg + 2.67 kg = 3.67 kg

(ii) \( 2H_2 + O_2 \rightarrow 2H_2O \)

\( 2 \times 1 \times 2 + 16 \times 2 = 2(1 \times 2 + 16) \)

\( i.e. \ 4 + 32 = 36 \)

or 1 kg + 8 kg = 9 kg

The two equations show that 1 kg of carbon requires 2.67 kg of oxygen and 1 kg of hydrogen requires 8 kg of oxygen for complete combustion.

\( \therefore \) O\(_2\) required to burn 0.624 kg of carbon = \( 0.624 \times 2.67 = 1.66 \) kg, and

O\(_2\) required to burn 0.042 kg of hydrogen = \( 0.042 \times 8 = 0.336 \) kg.

\( \therefore \) Total O\(_2\) required = 1.66 + 0.336 = 1.996 kg/kg of coal.
Oxygen already present in coal is 0.045 kg per kg of coal. This must be subtracted from the total oxygen required.

\[
\text{Net } O_2 \text{ required} = 1.996 - 0.045 = 1.951 \text{ kg per kg of coal.}
\]

As oxygen present in 100 kg of air is 23 kg,

Theoretical or minimum air required = 1.951 \times \frac{100}{23} = 8.5 \text{ kg per kg of coal.}

Alternatively, using eqn. (7.1),

Minimum air required = \frac{100}{23} \left[2.67C + 8H + S - O\right]

= \frac{100}{23} \left[(2.67 \times 0.0624) + (8 \times 0.042) - 0.045\right]

= 8.5 \text{ kg per kg of coal burnt (same as before)}

(ii) Before the actual air or total air supplied is calculated, the dry flue gas composition by volume has to be converted to analysis on mass basis as shown in the table below.

<table>
<thead>
<tr>
<th>Dry flue gas constituents</th>
<th>Volume in one m$^3$ of flue gas (a)</th>
<th>Molecular weight (b)</th>
<th>Proportional mass in kg (c) = (a) \times (b)</th>
<th>Actual mass in kg per kg of flue gas (d) = \frac{(c)}{\Sigma (c)}</th>
<th>Mass of carbon in kg per kg of flue gas (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>0.13</td>
<td>44</td>
<td>5.72</td>
<td>\frac{5.72}{30.314} = 0.1887</td>
<td>0.1887 \times \frac{12}{44} = 0.05146</td>
</tr>
<tr>
<td>CO</td>
<td>0.003</td>
<td>28</td>
<td>0.084</td>
<td>\frac{0.084}{30.314} = 0.0027</td>
<td>0.0027 \times \frac{12}{28} = 0.00118</td>
</tr>
<tr>
<td>C$_2$</td>
<td>0.06</td>
<td>32</td>
<td>1.92</td>
<td>\frac{1.92}{30.314} = 0.0634</td>
<td></td>
</tr>
<tr>
<td>N$_2$</td>
<td>0.807</td>
<td>28</td>
<td>22.59</td>
<td>\frac{22.59}{30.314} = 0.7452</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>= 1.000</td>
<td>-</td>
<td>= 30.314</td>
<td>= 1.0000</td>
<td>= 0.05264</td>
</tr>
</tbody>
</table>

Mass of flue gas produced = \frac{\text{Mass of carbon in 1 kg of coal}}{\text{Mass of carbon in 1 kg of flue gas}}

= \frac{0.624}{0.05264} = 11.85 \text{ kg/kg of coal.}

Mass of N$_2$ in the flue gas per kg of coal = 0.7452 \times 11.85 = 8.85 \text{ kg}

As nitrogen present in 100 kg of air is 77 kg,

Mass of air actually supplied = 8.85 \times \frac{100}{77} = 11.5 \text{ kg/kg of coal.}

(iii) Amount of excess air supplied per kg of coal burnt

= actual air supplied - minimum air required = 11.5 - 8.5 = 3 \text{ kg}

Problem-9 : The following is the percentage composition of a sample of coal on mass basis:

C, 82; H$_2$, 6; O$_2$, 9; and ash, 3.

Find: (a) the minimum mass of air required for complete combustion of 1 kg of
coal, and (b) the volumetric analysis of the products of combustion, if 10% excess air is supplied. Assume that air contains 23% oxygen on mass basis.

(a) Oxygen required to burn carbon and hydrogen may first be found.

The chemical reactions are:

(i) \[ C + O_2 \rightarrow CO_2 \]
    
\[
12 + 32 = 44
\]

or \[ 1 \text{ kg} + 2.67 \text{ kg} = 3.67 \text{ kg} \]

(ii) \[ 2H + O_2 \rightarrow 2H_2O \]
    
\[
4 + 32 = 36
\]

or \[ 1 \text{ kg} + 8 \text{ kg} = 9 \text{ kg} \]

The two equations show that 1 kg of carbon requires 2.67 kg of oxygen and 1 kg of hydrogen requires 8 kg of oxygen for complete combustion.

\[ \therefore O_2 \text{ required to burn } 0.82 \text{ kg of } C = 0.82 \times 2.67 \text{ kg}, \text{ and} \]

\[ O_2 \text{ required to burn } 0.06 \text{ kg of } H_2 = 0.06 \times 8 \text{ kg} \]

\[ \therefore \text{Total oxygen required} = (0.82 \times 2.67) + (0.06 \times 8) = 2.67 \text{ kg/kg of coal}. \]

The oxygen already present in 1 kg of coal must be subtracted from the total oxygen required.

\[ \therefore \text{Net theoretical } O_2 \text{ required to burn } 1 \text{ kg of coal} = 2.67 - 0.09 = 2.58 \text{ kg per kg of coal}. \]

As oxygen present in 100 kg of air is 23 kg,

Theoretical or minimum air required to burn 1 kg of coal completely

\[
\frac{100}{23} \times 2.58 = 11.21 \text{ kg/kg of coal.}
\]

(b) As 10% excess of air is supplied,

Excess air supplied per kg of coal = 0.1 \times 11.21 = 1.211 kg

\[ \therefore \text{Actual air supplied, per kg of coal} = \text{Minimum air required} + \text{Excess air supplied} = 11.21 + 1.121 = 12.331 \text{ kg}. \]

The products of combustion (wet) contain carbon dioxide, water vapour, oxygen and nitrogen. We must now determine the products of combustion as follows:

- Mass of \( CO_2 \) formed per kg of coal = 3.67 \( C \) = 3.67 \( C \) \times 0.82 = 3.01 kg.
- Mass of \( H_2O \) formed per kg of coal = 9\( H_2 \) = 9 \times 0.06 = 0.54 kg.
- Since, excess air has been supplied, excess oxygen will appear in the products of combustion. Hence, mass of excess \( O_2 \) per kg of coal

\[
\frac{23}{100} \times \text{excess air supplied} = 0.23 \times 1.121 = 0.258 \text{ kg.}
\]

- Nitrogen will also appear in the products of combustion as it does not take part in the combustion process and passes directly into the flue gases.

Hence, the mass of nitrogen per kg of coal

\[
\frac{77}{100} \times \text{actual air supplied} = 0.77 \times 12.331 = 9.5 \text{ kg.}
\]

Hence, the products of combustion per kg of coal, will consists of the following:

\( CO_2 = 3.01 \text{ kg}; \) Water vapour \( (H_2O) = 0.54 \text{ kg}; \) \( O_2 = 0.258 \text{ kg}; \) \( N_2 = 9.5 \text{ kg.} \)
If the mass of each constituent is divided by its own molecular weight; the proportional volume of each constituent is obtained. The proportional volume of each constituent so obtained is then divided by the sum of proportionate volumes of all the constituents to obtain the volumetric analysis.

For obtaining percentage volumetric analysis of products of combustion, table is constructed as shown below:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Mass in kg (a)</th>
<th>Molecular weight (b)</th>
<th>Proportional volume (c) = (a) + (b)</th>
<th>% Volumetric analysis (d) = ( \frac{(c)}{\sum(c)} \times 100 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>3.01</td>
<td>44</td>
<td>0.0684</td>
<td>( \frac{0.0684}{0.4460} \times 100 = 15.32 )</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.54</td>
<td>18</td>
<td>0.0300</td>
<td>( \frac{0.0300}{0.4460} \times 100 = 6.73 )</td>
</tr>
<tr>
<td>O₂</td>
<td>0.258</td>
<td>32</td>
<td>0.0081</td>
<td>( \frac{0.0081}{0.4460} \times 100 = 1.82 )</td>
</tr>
<tr>
<td>N₂</td>
<td>9.5</td>
<td>28</td>
<td>0.3395</td>
<td>( \frac{0.3395}{0.4460} \times 100 = 76.13 )</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>0.4460</td>
<td>( \frac{0.4460}{0.4460} \times 100 = 100.00 )</td>
</tr>
</tbody>
</table>

Volumetric analysis of flue gases is,

\( CO₂, 15.32\% ; H₂O, 6.73\% ; O₂, 1.82\% ; and N₂, 76.13\% . \)

**Problem-10**: The following is the percentage composition of coal on mass basis:

C, 90; H₂, 3.3; O₂, 3; S, 0.9; and remainder ash.

Calculate: (a) the theoretical air required to burn 1 kg of coal completely, and (b) the percentage composition of dry flue gases on mass and volume basis, if 50% excess air is supplied. (Assume that air contains 23% \( O₂ \) on mass basis).

(a) The chemical reactions are:

(i) \( C + O₂ = CO₂ \)

\[
\begin{align*}
12 + 32 & = 44 \\
1 + 2.67 & = 3.67
\end{align*}
\]

Equation (i) shows that 1 kg of carbon requires 2.67 kg of oxygen and produces 3.67 kg of \( CO₂ \).

\( \therefore \) 0.9 kg of carbon requires \( 0.9 \times 2.67 = 2.4 \) kg of oxygen, and produces 

\( 0.9 \times 3.67 = 3.303 \) kg of \( CO₂ \).

Equation (ii) shows that 1 kg of hydrogen requires 8 kg of oxygen and produces 9 kg of water vapour (\( H₂O \)).

\( \therefore \) 0.033 kg of hydrogen requires \( 0.033 \times 8 = 0.264 \) kg of oxygen and produces

\( 0.033 \times 9 = 0.297 \) kg of \( H₂O \).

Equation (iii) shows that 1 kg of sulphur requires 1 kg of oxygen and produces 2 kg of sulphur dioxide.

\( \therefore \) 0.009 kg of sulphur requires \( 0.009 \times 2 = 0.018 \) kg of sulphur dioxide.
Hence, total oxygen required per kg of coal

\[ = 2.4 + 0.264 + 0.009 = 2.673 \text{ kg}. \]

But, 0.03 kg of oxygen is already present in 1 kg of coal.

\[ \therefore \text{Net oxygen required for complete combustion of 1 kg of coal} \]

\[ = 2.673 - 0.03 = 2.643 \text{ kg/kg of coal}. \]

As 23 kg of oxygen is present in 100 kg of air, theoretical or minimum air required

\[ = 2.643 \times \frac{100}{23} = 11.5 \text{ kg/kg of coal}. \]

i.e. minimum mass of air necessary for complete combustion of 1 kg of coal is 11.5 kg.

(b) As 50% excess of air is supplied, air actually supplied

\[ = 11.5 \times 1.5 = 17.25 \text{ kg/kg of coal}. \]

\[ \therefore \text{Excess air supplied} = 17.25 - 11.5 = 5.75 \text{ kg/kg of coal}. \]

Since, excess air has been supplied, excess oxygen will appear in the products of combustion.

Hence, oxygen present in the products of combustion will be given by

\[ 0.23 \times \text{excess air supplied} = 0.23 \times 5.75 \text{ kg per kg of coal}. \]

Nitrogen will also appear in the products of combustion.

Hence, nitrogen in the products of combustion will be given by

\[ 0.77 \times \text{actual air supplied} = 0.77 \times 17.25 \text{ kg/kg of coal}. \]

The products of combustion, per kg of coal, will consists of

\[ \text{CO}_2 = C \times 3.67 = 0.9 \times 3.67 = 3.303 \text{ kg} \]
\[ \text{H}_2\text{O} = H_2 \times 9 = 0.033 \times 9 = 0.297 \text{ kg} \]
\[ \text{SO}_2 = S \times 2 = 0.009 \times 2 = 0.018 \text{ kg} \]
\[ \text{Oxygen in excess air} = 0.23 \times 5.75 = 1.322 \text{ kg} \]

Nitrogen in air actually supplied = 0.77 x 17.25 = 13.282 kg

As water vapour (H\textsubscript{2}O) is wet gas, dry flue gases contained in the products of combustion are:

\[ \text{CO}_2 = 3.303 \text{ kg}; \text{SO}_2 = 0.018 \text{ kg}; \text{O}_2 = 1.322 \text{ kg}; \text{and N}_2 = 13.282 \text{ kg}, \]

\[ \therefore \text{Total mass of dry flue gases} = 3.303 + 0.018 + 1.322 + 13.282 \]

\[ = 17.925 \text{ kg/kg of coal}. \]

Hence, percentage composition of dry flue gases on mass basis is,

\[ \text{CO}_2 = \frac{3.303}{17.925} \times 100 = 18.42\%; \text{SO}_2 = \frac{0.018}{17.925} \times 100 = 0.1\%; \]
\[ \text{O}_2 = \frac{1.322}{17.925} \times 100 = 7.38\%; \text{N}_2 = \frac{13.282}{17.925} \times 100 = 74.1\%. \]

Using tabular method (shown below) of converting percentage analysis on mass basis to volumetric analysis of dry flue gases, we have,
### Volumetric Analysis of Dry Flue Gases

- \( \text{CO}_2 = 12.7\% \)
- \( \text{SO}_2 = 0.05\% \)
- \( \text{O}_2 = 7\% \)
- \( \text{N}_2 = 80.25\% \)

### Problem-11

A sample of oil fuel was found to be composed of 80\% carbon and 20\% hydrogen. If 6.25\% of the carbon contained in one kg of fuel is burned to carbon monoxide due to incomplete combustion and remainder to carbon dioxide and if 40 per cent excess air was supplied per kg of fuel burnt, determine:

(a) the theoretical air required for complete combustion of 1 kg of oil fuel,
(b) the excess oxygen in the flue gases per kg of oil fuel burnt,
(c) the percentage analysis on mass basis of the total products of combustion,
(d) the percentage volumetric analysis of the total products of combustion.

#### Solution

(a) The chemical reactions are:

(i) \( \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \)
(ii) \( 2\text{C} + \text{O}_2 \rightarrow \text{CO} \)
(iii) \( 2\text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O} \)

\[
12 + 32 = 44 \quad 24 + 32 = 56 \quad 4 + 32 = 36
\]

or \( 1 + 2.67 = 3.67 \) \quad or \( 1 + 1.33 = 2.33 \) \quad or \( 1 + 8 = 9 \)

From eqns. (i) and (iii),

- Oxygen required to burn completely carbon and hydrogen
  \[
  = (0.8 \times 2.67) + (0.2 \times 8) = 3.725 \text{ kg per kg of fuel.}
  \]

- Theoretical air required for complete combustion of 1 kg oil fuel
  \[
  = 3.725 \times \frac{100}{23} = 16.25 \text{ kg.}
  \]

(b) As 40\% excess air is supplied,

Actual air supplied = \( 16.25 \times 1.4 = 22.75 \text{ kg} \), of this air 77\% is \( \text{N}_2 \) and 23\% is \( \text{O}_2 \).

\[
\text{N}_2 \text{ in the total air supplied} = 22.75 \times 0.77 = 17.52 \text{ kg, and}
\]

\[
\text{O}_2 \text{ in the total air supplied} = 22.75 \times 0.23 = 5.23 \text{ kg.}
\]

Per kg of oil fuel burnt, \( 0.8 \times 0.0625 = 0.05 \text{ kg} \) of \( \text{C} \) was burnt to \( \text{CO} \),

\[
0.8 (1 - 0.0625) = 0.75 \text{ kg} \text{ of } \text{C} \text{ was burnt to } \text{CO}_2 \text{ and}
\]

\[
0.2 \text{ kg} \text{ of } \text{H}_2 \text{ was burnt to } \text{H}_2\text{O.}
\]

\[
\text{O}_2 \text{ actually used to burn 1 kg of oil fuel}
= (0.05 \times 1.33) + (0.75 \times 2.67) + (0.2 \times 8) = 3.67 \text{ kg.}
\]
Excess oxygen in the flue gases = $O_2$ in the total air supplied \( - O_2 \) actually used 
\[ = 5.23 - 3.67 = 1.56 \text{ kg per kg of oil fuel} \]

(c) The wet products of combustion are: $CO_2$, $CO$, $H_2O$, $N_2$ and excess $O_2$

Their masses can be calculated as under:

\[
\begin{align*}
CO_2 &= C \times 3.67 = 0.75 \times 3.67 = 2.753 \text{ kg} \\
CO &= C \times 2.33 = 0.05 \times 2.33 = 0.117 \text{ kg} \\
H_2O &= H_2 \times 9 = 0.2 \times 9 = 1.8 \text{ kg} \\
\text{Excess } O_2 &= 1.56 \text{ kg} \\
N_2 &= 17.52 \text{ kg}
\end{align*}
\]

Total mass of wet products of combustion = 23.75 kg per kg of oil fuel

Hence, percentage analysis on mass basis of wet products of combustion is,

\[
\begin{align*}
CO_2 &= \frac{2.753}{23.75} \times 100 = 11.37; \quad CO = \frac{0.117}{23.75} \times 100 = 0.49; \quad H_2O = \frac{1.8}{23.75} \times 100 = 7.58; \\
\text{Excess } O_2 &= \frac{1.56}{23.75} \times 100 = 6.56; \quad N_2 = \frac{17.52}{23.75} \times 100 = 73.8.
\end{align*}
\]

(d) The mass of each constituent when divided by its molecular weight, proportional volume of constituent is obtained. The proportional volume so obtained is then divided by the sum of proportionate volumes to obtain the analysis by volume (see table).

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Mass in kg (a)</th>
<th>Molecular weight (b)</th>
<th>Proportional volume (c) = (a) + (b)</th>
<th>Percentage volumetric analysis ( \frac{(c)}{\Sigma (c)} \times 100 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CO_2$</td>
<td>2.753</td>
<td>44</td>
<td>0.06248</td>
<td>0.06248 \times 100 = 7.426</td>
</tr>
<tr>
<td>$CO$</td>
<td>0.117</td>
<td>28</td>
<td>0.00418</td>
<td>0.00418 \times 100 = 0.497</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>1.8</td>
<td>18</td>
<td>0.1000</td>
<td>0.1000 \times 100 = 11.90</td>
</tr>
<tr>
<td>$O_2$</td>
<td>1.56</td>
<td>32</td>
<td>0.04875</td>
<td>0.04875 \times 100 = 5.79</td>
</tr>
<tr>
<td>$N_2$</td>
<td>17.52</td>
<td>28</td>
<td>0.6256</td>
<td>0.6256 \times 100 = 74.387</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>23.75</strong></td>
<td><strong>-</strong></td>
<td><strong>0.841</strong></td>
<td><strong>0.841</strong> \times 100 = 100.00</td>
</tr>
</tbody>
</table>

Volumetric analysis of the products of combustion is,

$CO_2$: 7.426%; $CO$: 0.497%; $H_2O$: 11.9%; $O_2$: 5.79%; $N_2$: 74.387%

7.12 Determination of Volumetric Analysis of Flue Gases

The Orsat apparatus is very convenient for analysing flue gases from the boiler or engine on the spot. In its simplest form the apparatus is arranged for the absorption of $CO_2$, $CO$ and $O_2$. The nitrogen content of the gas is obtained by difference.

The schematic diagram of Orsat apparatus is shown in fig 7-1. The essential parts of this apparatus are:

- A measuring burette, called *eudiometer*, surrounded by a water filled jacket to maintain constant temperature during analysing operations.
Three absorption double flasks for the absorption of \( \text{CO}_2 \), \( \text{O}_2 \) and \( \text{CO} \). For \( \text{CO}_2 \), the flask at the right (near eudiometer) contains 1 part of caustic soda (\( \text{NaOH} \)) or caustic potash (\( \text{KOH} \)) in 2 parts of water by mass. For \( \text{O}_2 \), the flask in the middle contains one part of pyrogallic acid in three parts of water, and 24 parts of either caustic soda or potash in 16 parts of water by mass. For \( \text{CO} \), the flask at the left contains a solution of cuprous chloride in hydrochloric acid, which is prepared by dissolving copper oxide (\( \text{CuO} \)) in about twenty times its mass of strong hydrochloric acid and allowing it to stand in a corked flask containing copper wire until the solution is colourless. The reagent flask contains a number of lengths of glass tubes in order to increase the surface of the reagent exposed to the gases. At the entrance, each flask is provided with a cock. A three-way cock is provided for giving straight-through connection and also connection to the atmosphere.

An aspirator bottle connected to the lower end of the eudiometer is provided for drawing (taking in) exhaust or flue gases in the apparatus.

7.12.1 Procedure for operating the Orsat Apparatus: In order to obtain the sample of exhaust or flue gases, the reagents in the flasks are adjusted to some known level and cocks shut. The three-way cock is then opened to the atmosphere and the aspirator bottle raised until water is discharged to atmosphere. Three-way cock is then turned to the ‘through’ position and aspirator lowered, thus drawing in the flue gases from the boiler or engine through a suitable connection near the base of the chimney in the case of a boiler, and near the exhaust valve in the case of I.C. engine. The operation should be repeated several times, the aspirated gas being discharged to atmosphere in order to make sure that all air has been cleared from the connecting tubing. Having drawn in 100 c c. of the representative sample of gases, the three-way cock is closed.

The percentage of \( \text{CO}_2 \) is first obtained by opening the cock on the flask at the
right and forcing gases from the eudiometer into the flask by raising the aspirator bottle. When
the gas is withdrawn by again lowering the aspirator, the cock on the flask is closed when the
reagent reaches its original level. This is repeated several times, the reduction in volume as
indicated by eudiometer being noted. When no further decrease is noted, all the \( CO_2 \) is absorbed and the total decrease in volume gives the percentage of \( CO_2 \) present in the flue gases.

Oxygen \((O_2)\) is next absorbed in a similar manner in the flask, and finally carbon monoxide \((CO)\) is absorbed in the flask at the left. After the absorption of \( CO_2, O_2 \) and \( CO \), the gas remaining is assumed to be nitrogen.

When taking eudiometer reading, care should be taken to see that the water level
is same in both the eudiometer and the aspirator bottle.

7.13 Heat Carried away by Flue Gases

With chimney draught in a boiler plant, it is necessary for the flue gases to leave the boiler at a considerably higher temperature above that of the steam produced. This high temperature as well as the excess air causes loss of heat amounting to about 25% of the total heat produced by the fuel. This loss is due to:

.. The heat carried away by the dry products of combustion, and

.. Heat carried away by the steam in the flue gases.

The formation of steam in the flue gases may be due to:

— Combustion of the free hydrogen in the fuel,
— Vaporisation of moisture in the fuel,
— Moisture contained in the air supplied for combustion, and
— Moisture contained in excess air supplied.

(i) Heat carried away by dry flue gases or products of combustion:

If \( m_g = \) mass of dry flue gases in kg per kg of fuel burnt,

\[ k_p = \text{mean specific heat of dry flue gases in kJ/kg K}, \]

\[ t_i = \text{temperature of flue gases leaving the boiler in } °C, \text{ and} \]

\[ t_o = \text{temperature of the boiler room in } °C. \]

Then, heat carried away by dry flue gases produced per kg of fuel burnt

\[
= m_g \times k_p (t_i - t_o) \text{ kJ}
\]

(ii) Heat carried away by steam in flue gases:

The enthalpy (total heat) of steam in flue gases will correspond to its partial pressure because it is now one of the constituents of a mixture of steam and other gases.

If the method of solution by partial pressures is applied to products of combustion of a fuel, it will be found that the partial pressure of the steam is very low (usually less than 0.1 bar) and the steam is in a highly superheated state.

The exact value of partial pressure of steam \((p_s)\) can be determined as follows:

For 1 kg of flue gases, \(10^5\ p_{t}v_{t} = RT_{t}\)

where \( T_{t} = \text{absolute temperature of flue gases} \).

Knowing \( T_{t} \) and taking pressure \( p_t \) as atmospheric (1.01325 bar), and \( R \) as
287 J/kg K, volume $v_f$ can be calculated for 1 kg of flue gases.

Now, according to Dalton's Law, steam also occupies volume $v_f$ m$^3$ at its partial pressure $p_s$ and temperature $t_f^\circ$C. (For Dalton's law refer volume II).

If $m_s$ is the mass of steam contained in one kg of flue gases,

then volume of 1 kg of superheated steam, $v_{sup} = \frac{v_f}{m_s}$ m$^3$.

Now, by using steam tables for superheated steam and solving by trial, the partial pressure of steam $p_s$ can be found. Knowing $p_s$ and $t_f$ of steam, its enthalpy (total heat) can be evaluated.

If $m_s =$ mass of steam formed in kg per kg of fuel burnt,

$H_{sup} =$ enthalpy (total heat) of superheated steam in kJ/kg at the temperature of flue gases $t_f^\circ$C and its partial pressure $p_s$, and

$h_0 =$ enthalpy (sensible heat) of water in kJ/kg at the boiler room temperature, $t_o^\circ$C,

Then, the heat carried away by the steam per kg of fuel burnt = $m_s \ (H_{sup} - h_0)$ kJ ... (7.3)

Heat carried away by water vapour (steam) can be estimated with sufficient accuracy by assuming partial pressure of steam ($p_s$) to be atmospheric (see illustrative problem-14).

Total heat carried away by products of combustion per kg of fuel burnt = heat carried away by dry flue gases + heat carried away by steam in flue gases

$= m_g \times k_p \ (t_f - t_o) + m_s \ (H_{sup} - h_0)$ kJ per kg of fuel ... (7.4)

Problem-12: The percentage composition of a sample of coal on mass basis is as follows: $C$, 85; $H$, 12; and $O_2$, 3.

Determine the theoretical or minimum air required for complete combustion of 1 kg of coal. If the total air supplied is 1.5 times the minimum air required, calculate the mass of dry products of combustion per kg of coal burned and the heat carried away by the dry products of combustion leaving the boiler per kg of coal burned, if the average specific heat of dry flue gases is 1.005 kJ/kg K and the temperature of flue gases is 375$^\circ$C and the boiler house temperature is 25$^\circ$C.

Using eqn. (7.1), minimum air required per kg of coal burned

$= \frac{100}{23} \ [2.67C + 8H + S - O] = \frac{100}{23} \ [(2.67 \times 0.85) + (8 \times 0.12) - 0.03] = 13.91$ kg

:. Actual air supplied per kg of coal = $13.91 \times 1.5 = 20.865$ kg and

Excess air supplied per kg of coal = $13.91 \times 0.5 = 6.955$ kg.

The dry products of combustion per kg of coal will consist of:

CO$_2$ produced = $C \times 3.67 = 0.85 \times 3.67 = 3.2$ kg

Excess O$_2$ = Excess air $\times 0.23 = 6.955 \times 0.23 = 1.6$ kg

$N_2 = Actual \ air \times 0.77 = 20.865 \times 0.77 = 16.07$ kg

Total mass of dry products of combustion = 20.87 kg per kg of coal.

Using eqn. (7.2), heat carried away by dry flue gases per kg of coal burned

$= m_g \times k_p \times (t_f - t_o) = 20.87 \times 1.005 \times (375 - 25) = 7341$ kJ per kg of coal.
Problem-13: The fuel supplied to a boiler has the following composition on mass basis:

- 85%, carbon; 13%, hydrogen; 2%, oxygen.

The air supplied is 60% in excess of that theoretically required for complete combustion. Estimate the volumetric composition of the dry flue gases. If the temperature of the boiler house is 15°C and the temperature of the flue gases is 330°C, estimate the heat carried away by the flue gases leaving the boiler plant. Assume $k_p$ of dry flue gases to be 1.005 kJ/kg K and enthalpy of water vapour in the flue gases to be 2,680 kJ/kg. (Assume that air contains 23% $O_2$ on mass basis).

Using eqn. (7.1), theoretical or minimum air required per kg of fuel

$$\frac{100}{23} \times (2.67C + 8H + S - O) = \frac{100}{23} \times [(2.67 \times 0.85) + (8 \times 0.13) - 0.02] = 14.3 \text{ kg}$$

As 60% excess air is supplied,

- Excess air supplied per kg of fuel $= 0.6 \times 14.3 = 8.58 \text{ kg}$, and
- Actual air supplied per kg of fuel $= 1.6 \times 14.3 = 22.88 \text{ kg}$.

Dry products of combustion per kg of fuel will consist of:

(i) Carbon dioxide $= 3.67C = 3.67 \times 0.85 = 3.12 \text{ kg}$.

(ii) Excess $O_2 = 0.23 \times$ excess air supplied per kg of fuel $= 0.23 \times 8.58 = 1.97 \text{ kg}$.

(iii) Nitrogen $= 0.77 \times$ actual air supplied per kg of fuel $= 0.77 \times 22.88 = 17.61 \text{ kg}$.

:. Total mass of dry flue gases $=$ mass of $CO_2 +$ mass of excess $O_2 +$ mass of $N_2$

$= 3.12 + 1.97 + 17.61 = 22.7 \text{ kg}$ per kg of fuel.

Hence, percentage composition of dry flue gases on mass basis is,

- $CO_2 = \frac{3.12}{22.7} \times 100 = 13.75\%$

- $O_2 = \frac{1.97}{22.7} \times 100 = 8.67\%$

- $N_2 = \frac{17.61}{22.7} \times 100 = 77.58\%$

Total $= 100.00\%$

Using tabular method (shown below) of converting analysis on mass basis into volumetric analysis of dry flue gases, we have

<table>
<thead>
<tr>
<th>Constituent</th>
<th>% Composition on mass basis (a)</th>
<th>Molecular weight (b)</th>
<th>Relative volume (c) $= \frac{(a)}{(b)}$</th>
<th>Percentage composition by vol. $(d) = \frac{(c)}{\sum (c)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CO_2$</td>
<td>13.75</td>
<td>44</td>
<td>0.312</td>
<td>$\frac{0.312}{3.351} = 0.093 \times 100 = 9.3$</td>
</tr>
<tr>
<td>$O_2$</td>
<td>8.67</td>
<td>32</td>
<td>0.271</td>
<td>$\frac{0.271}{3.351} = 0.081 \times 100 = 8.1$</td>
</tr>
<tr>
<td>$N_2$</td>
<td>77.58</td>
<td>28</td>
<td>2.768</td>
<td>$\frac{2.768}{3.351} = 0.826 \times 100 = 82.6$</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td></td>
<td>$= 3.351$</td>
<td>$= 100.00$</td>
</tr>
</tbody>
</table>
Volumetric analysis of the dry flue gases is,

\[ CO_2 = 9.3\%; \quad O_2 = 8.1\%; \quad \text{and} \quad N_2 = 82.6\%. \]

Total mass of dry flue gases per kg of fuel, \( m_g = 22.7 \) kg.

Using eqn. (7.2), Heat carried away by dry flue gases per kg of fuel

\[ = m_g \times k_p \times (t_f - t_o) = 22.7 \times 1.005 \times (330 - 15) = 7,185 \text{ kJ/kg of fuel.} \]

Mass of water vapour (H_{2O}) formed in the combustion process

\[ = 9H = 9 \times 0.13 = 1.17 \text{ kg/kg of fuel} \]

\[ \therefore \text{Heat carried away by water vapour} = 1.17 \times 2,680 = 3,135.6 \text{ kJ/kg of fuel} \]

\[ \therefore \text{Total heat carried away by the flue gases leaving the boiler} = 7,185 + 3,135.6 = 10,320.6 \text{ kJ per kg of fuel.} \]

Problem-14: The composition of a sample of coal shows 0.872 kg of carbon and 0.042 kg of hydrogen per kg of coal. If the air supplied is 1.52 times the minimum air, calculate the heat carried away by the products of combustion per kg of coal, if they escape to the chimney at a temperature of 350°C. Take specific heat of CO_{2}, O_{2}, N_{2}, and steam as 0.917, 1.047, 1.022, and 1.863 kJ/kg K respectively. Assume steam to be at atmospheric pressure. The boiler room temperature is 15°C. Air contains 23% O_{2} on mass basis.

To find minimum mass of air required per kg of coal:

\[ O_2 \text{ required to burn } C = C \times 2.67 = 0.872 \times 2.67 = 2.33 \text{ kg} \]

\[ O_2 \text{ required to burn } H_2 = H_2 \times 8 = 0.042 \times 8 = 0.34 \text{ kg} \]

Total \( O_2 \) required for complete combustion of 1 kg of coal = 2.67 kg

\[ \therefore \text{Mass of minimum air required} = 2.67 \times 100/23 = 11.61 \text{ kg} \]

As the total air supplied is 1.52 times the minimum required,

\[ \text{Total air supplied per kg of coal} = 11.61 \times 1.52 = 17.65 \text{ kg} \]

\[ \therefore \text{Excess air supplied} = 17.65 - 11.61 = 6.04 \text{ kg} \]

To find the mass of products of combustion per kg of coal:

\[ CO_2 = 0.872 \times 3.67 = 3.2 \text{ kg}; \quad N_2 = 17.65 \times 0.77 = 13.58 \text{ kg.} \]

\[ O_2 \text{ from excess air} = 6.04 \times 0.23 = 1.39 \text{ kg}; \quad \text{and steam} = 0.042 \times 9 = 0.38 \text{ kg.} \]

Heat carried away by dry products of combustion per degree centigrade temperature difference = 3.2 \times 0.971 + 1.39 \times 1.047 + 13.58 \times 1.022 = 18.267 \text{ kJ.} \]

Total heat carried away by dry products of combustion

\[ = 18.267 \times (350 - 15) = 6,119.5 \text{ kJ/kg of coal.} \]

Using eqn. (7.3)

Heat carried away by steam at atmospheric pressure and 350°C

\[ = m_s \times (H_{sup} - h_o) \]

\[ = 0.38 \times [(2,676.1 + 1.863 \times (350 - 100)) - 15 \times 4.187] = 1,170 \text{ kJ/kg of coal} \]

\[ \therefore \text{Total heat carried away by products of combustion per kg of coal} \]

\[ = 6,119.5 + 1,170 = 7,289.5 \text{ kJ/kg of coal.} \]
7.14 Volume of Minimum Air required for Complete Combustion of Gaseous Fuel

Problem-15: Calculate the volume of minimum air required to burn completely 1 m³ of a gaseous fuel having the following composition by volume: H₂, 14%; CH₄, 1%; CO, 24%; CO₂, 5%; O₂, 1%; and N₂, 55%. If 40% excess air is supplied, determine the actual volume of air supplied per m³ of gas. (Assume that air contains 21% O₂ by volume).

Reactions of combustion can be written as:

(i) \( 2H₂ + O₂ = 2H₂O \)

\[ 2 \text{ vol.} + 1 \text{ vol.} = 2 \text{ vol.} \]
\[ 1 \text{ m}³ + 1/2 \text{ m}³ = 1 \text{ m}³ \]

(ii) \( CH₄ + 2O₂ = CO₂ + 2H₂O \)

\[ 1 \text{ vol.} + 2 \text{ vol.} = 1 \text{ vol.} + 2 \text{ vol.} \]
\[ 1 \text{ m}³ + 2 \text{ m}³ = 1 \text{ m}³ + 2 \text{ m}³ \]

(iii) \( 2CO + O₂ = 2CO₂ \)

\[ 2 \text{ vol.} + 1 \text{ vol.} = 2 \text{ vol.} \]
\[ 1 \text{ m}³ + 1/2 \text{ m}³ = 1 \text{ m}³ \]

Equation (i) shows that 1 m³ of hydrogen requires 1/2 m³ of oxygen for complete combustion and the product of combustion will occupy 1 m³.

Equation (ii) shows that 1 m³ of CH₄ (marsh gas) requires 2 m³ of oxygen for complete combustion.

Equation (iii) shows that 1 m³ of carbon monoxide (CO) requires 1/2 m³ of oxygen for complete combustion.

Volume of \( O₂ \) required for complete combustion of \( H₂ \)

\[ = H₂ \times \frac{1}{2} = 0.14 \times \frac{1}{2} = 0.07 \text{ m}³ \]

from eqn. (i)

Volume of \( O₂ \) required for complete combustion of \( CH₄ \)

\[ = CH₄ \times 2 = 0.01 \times 2 = 0.02 \text{ m}³ \]

from eqn. (ii)

Volume of \( O₂ \) required for complete combustion of \( CO \)

\[ = CO \times \frac{1}{2} = 0.24 \times \frac{1}{2} = 0.12 \text{ m}³ \]

from eqn. (iii)

Total volume of \( O₂ \) required = 0.07 + 0.02 + 0.12 = 0.21 m³.

As \( O₂ \) already present in gaseous fuel is 0.01 m³,

Net \( O₂ \) required = 0.21 - 0.01 = 0.2 m³ per m³ of gas

As air contains 21% oxygen by volume, minimum volume of air required

\[ = 0.2 \times \frac{100}{21} = 0.953 \text{ m}³ \text{ per m}³ \text{ of gas.} \]

As 40% excess air is supplied, actual volume of air supplied

\[ = 0.953 \times 1.4 = 1.3342 \text{ m}³ \text{ per m}³ \text{ of gas.} \]

Problem-16: The following is the percentage composition of a gaseous fuel by volume:

\( H₂, 46; C₂H₄, 2.5; CH₄, 37.5; N₂, 45; CO, 7.5; \) and moisture, 2.

Determine the volume of minimum air required and the percentage volumetric composition of wet products of combustion. (Assume that air contains 21% \( O₂ \) by volume).

Reactions of combustion can be written as:
(i) \(2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}\)  
(iii) \(\text{CH}_4 + 2\text{O}_2 = \text{CO}_2 + 2\text{H}_2\text{O}\)  
(ii) \(\text{C}_2\text{H}_4 + 3\text{O}_2 = 2\text{CO}_2 + 2\text{H}_2\text{O}\)  
(iv) \(2\text{CO} + \text{O}_2 = 2\text{CO}_2\)

2 vol. + 1 vol. = 2 vol.  
1 vol. + 3 vol. = 2 vol. + 2 vol.  
1 m³ + 1/2 m³ = 1 m³  
1 m³ + 3 m³ = 2 m³ + 2 m³

Volume of \(\text{O}_2\) required to burn \(\text{H}_2\): \(\text{H}_2 \times \frac{1}{2} = 0.46 \times \frac{1}{2} = 0.23\) m³ from eqn. (i)

Volume of \(\text{O}_2\) required to burn \(\text{C}_2\text{H}_4\): \(\text{C}_2\text{H}_4 \times 3 = 0.025 \times 3 = 0.075\) m³ from eqn. (ii)

Volume of \(\text{O}_2\) required to burn \(\text{CH}_4\): \(\text{CH}_4 \times 2 = 0.375 \times 2 = 0.75\) m³ from eqn. (iii)

Volume of \(\text{O}_2\) required to burn \(\text{CO}\): \(\text{CO} \times \frac{1}{2} = 0.075 \times \frac{1}{2} = 0.0375\) m³ from eqn. (iv)

Total volume of \(\text{O}_2\) required per m³ of gas = \(\frac{0.23 + 0.075 + 0.75 + 0.0375}{2} = 1.0925\) m³

\[\therefore\] Minimum volume of air required = \(1.0925 \times \frac{100}{21} = 5.202\) m³ per m³ of gas.

The dry products of combustion will consist of:
- \(\text{CO}_2\) by combustion of \(\text{C}_2\text{H}_4, \text{CH}_4\) and \(\text{CO}\), and
- \(\text{N}_2\) from fuel gas, and from air supplied.

Volume of dry product of combustion (\(\text{CO}_2\)):

\(\text{CO}_2\) from \(\text{C}_2\text{H}_4\): \(\text{C}_2\text{H}_4 \times 2 = 0.025 \times 2 = 0.05\) m³ from eqn. (ii)

\(\text{CO}_2\) from \(\text{CH}_4\): \(\text{CH}_4 \times 1 = 0.375 \times 1 = 0.375\) m³ from eqn. (iii)

\(\text{CO}_2\) from \(\text{CO}\): \(\text{CO} \times 1 = 0.075 \times 1 = 0.075\) m³ from eqn. (iv)

Total volume of \(\text{CO}_2\) formed = 0.5 m³

Volume of dry product of combustion (\(\text{N}_2\)):

\(\text{N}_2\) in gaseous fuel (by given composition) = 0.045 m³

\(\text{N}_2\) in air supplied = \(5.202 \times \frac{79}{100} = 4.11\) m³

Total volume of \(\text{N}_2\) = 4.155 m³

Volume of wet products of combustion (\(\text{H}_2\text{O}\)):

Steam (\(\text{H}_2\text{O}\)) from \(\text{H}_2\): \(\text{H}_2 \times 1 = 0.46 \times 1 = 0.46\) m³ from eqn. (i)

Steam (\(\text{H}_2\text{O}\)) from \(\text{C}_2\text{H}_4\): \(\text{C}_2\text{H}_4 \times 2 = 0.025 \times 2 = 0.05\) m³ from eqn. (ii)

Steam (\(\text{H}_2\text{O}\)) from \(\text{CH}_4\): \(\text{CH}_4 \times 2 = 0.375 \times 2 = 0.75\) m³ from eqn. (iii)

Steam (\(\text{H}_2\text{O}\)) from moisture

in the gaseous fuel (by given composition) = 0.02 m³

Total volume of steam formed = 1.28 m³

Thus, the volume of wet products of combustion is,

\(\text{CO}_2\) = 0.5 m³; \(\text{N}_2\) = 4.155 m³; \(\text{H}_2\text{O}\) = 1.28 m³

Total volume of wet products of combustion = 0.5 + 4.155 + 1.28 = 5.935 m³

Hence, volumetric analysis of wet products of combustion is,
\[ \text{CO}_2 = \frac{0.5}{5.935} \times 100 = 8.4\%; \quad \text{N}_2 = \frac{4.155}{5.935} \times 100 = 70\%; \text{ and} \]
\[ \text{H}_2\text{O} = \frac{1.28}{5.935} \times 100 = 21.6\% \]

Volumetric analysis of wet products of combustion is,

\[ \text{CO}_2 = 8.4\%; \quad \text{N}_2 = 70\%; \text{ and } \text{H}_2\text{O} = 21.6\% \]

**Problem-17:** The percentage composition of a producer gas by volume found from its analysis was reported as:

\[ \text{H}_2 = 14; \quad \text{CH}_4 = 2; \quad \text{CO} = 22; \quad \text{CO}_2 = 5; \quad \text{O}_2 = 2; \text{ and } \text{N}_2 = 55. \]

Calculate: (a) the volume of minimum air required for the complete combustion of 1 m³ of this gas, and (b) the volumetric analysis of dry products of combustion, if 40% excess air is supplied. (Assume that air contains 21% oxygen by volume).

(a) Reactions of combustion can be written as:

(i) \[ 2\text{H}_2 + \text{O}_2 \quad = \quad 2\text{H}_2\text{O} \]

\[ 2 \text{ vol.} + 1 \text{ vol.} = 2 \text{ vol.} \]

\[ 1 \text{ m}^3 + \frac{1}{2} \text{ m}^3 = 1 \text{ m}^3 \]

(ii) \[ 2\text{CO} + \text{O}_2 \quad = \quad 2\text{ CO}_2 \]

\[ 2 \text{ vol.} + 1 \text{ vol.} = 2 \text{ vol.} \]

\[ 1 \text{ m}^3 + \frac{1}{2} \text{ m}^3 = 1 \text{ m}^3 \]

(iii) \[ \text{CH}_4 + 2\text{O}_2 \quad = \quad 2\text{H}_2\text{O} + \text{CO}_2 \]

\[ 1 \text{ vol.} + 2 \text{ vol.} = 2 \text{ vol.} + 1 \text{ vol.} \]

\[ 1 \text{ m}^3 + 2 \text{ m}^3 = 2 \text{ m}^3 + 1 \text{ m}^3 \]

Equation (i) shows that 1 m³ of hydrogen requires \( \frac{1}{2} \) m³ of oxygen for complete combustion.

\[ \therefore \text{ Oxygen required for complete combustion of hydrogen } = \frac{1}{2} \text{ H}_2 = 0.5 \times 0.14 = 0.07 \text{ m}^3. \]

Equation (ii) shows that 1 m³ of carbon monoxide requires \( \frac{1}{2} \) m³ of oxygen for complete combustion.

\[ \therefore \text{ Oxygen required for complete combustion of carbon monoxide } = 0.5 \times 0.22 = 0.11 \text{ m}^3. \]

Equation (iii) shows that 1 m³ of \( \text{CH}_4 \) requires 2 m³ of oxygen for complete combustion.

\[ \therefore \text{ Oxygen required for complete combustion of } \text{CH}_4 = 2 \times \text{CH}_4 = 2 \times 0.02 = 0.04 \text{ m}^3. \]

\[ \therefore \text{ Total volume of oxygen required } = 0.07 + 0.11 + 0.04 = 0.22 \text{ m}^3. \]

The oxygen available in the fuel gas must be subtracted from the total oxygen required.

\[ \therefore \text{ Net oxygen to be supplied by air } = 0.22 - 0.02 = 0.2 \text{ m}^3. \]

As air contains 21% oxygen by volume,

Volume of minimum air required for complete combustion of 1 m³ of producer gas.

\[ = 0.2 \times \frac{100}{21} = 0.953 \text{ m}^3. \]

(b) As 40% excess of air is supplied, actual volume of air supplied = 0.953 \times 1.4 = 1.335 \text{ m}^3.

The dry products of combustion will consist of:

- \text{CO}_2 from fuel gas, and by the combustion of \text{CH}_4 and \text{CO},
— Oxygen due to excess air supplied, and
— Nitrogen from the actual air supplied, and from the fuel gas,
— Carbon dioxide from gaseous fuel (by given composition) = 0.05 m³

\[ CO_2 \text{ formed due to combustion of } CH_4 = CH_4 \times 1 = 0.02 \times 1 = 0.02 \text{ m}^3 \]

from eqn. (ii)

\[ CO_2 \text{ formed due to combustion of } CO = CO \times 1 = 0.22 \times 1 = 0.22 \text{ m}^3 \]

from eqn. (iii)

:. Total volume of \( CO_2 \) formed in the flue gas by the combustion of 1 m³ of fuel gas
\( = 0.05 + 0.02 + 0.22 = 0.29 \text{ m}^3 \)

— Volume of excess oxygen in flue gas
\( = (\text{Actual air supplied} - \text{Minimum air required}) \times 0.21 \)
\( = (1.335 - 0.953) \times 0.21 = 0.0802 \text{ m}^3 \)

— Nitrogen from producer gas (by given composition) = 0.55 m³

Nitrogen from the actual air supplied
\( = 0.79 \times \text{actual air supplied} = 0.79 \times 1.335 = 1.054 \text{ m}^3 \)

:. Total volume of nitrogen in flue gas = 0.55 + 1.054 = 1.604 m³.

Hence, the volume of dry products of combustion per m³ of producer gas is

\[ \text{Carbon dioxide} = 0.29 \text{ m}^3 \]
\[ \text{Oxygen} = 0.0802 \text{ m}^3 \]
\[ \text{Nitrogen} = 1.604 \text{ m}^3 \]

Total volume of dry products of combustion = 1.9742 m³

Hence, volumetric analysis of dry products of combustion is

\[ \text{Carbon dioxide} = \frac{0.29}{1.9742} \times 100 = 14.7\% \]
\[ \text{Oxygen} = \frac{0.0802}{1.9742} \times 100 = 4.06\% \]
\[ \text{Nitrogen} = \frac{1.604}{1.9742} \times 100 = 81.24\% \]

Total = 100\%

Problem-18: A gas engine uses producer gas which has a percentage volumetric analysis as follows: \( CO = 11; H_2 = 29; CH_4 = 18; CO_2 = 16.1; \) and \( N_2 = 42.1 \). Calculate the volume of minimum air required to completely burn one cubic metre of this gas.

If the air supplied to the gas engine is 50% in excess of this quantity, what is the calorific value of one cubic metre of cylinder mixture? Calorific values of \( CO, H_2 \) and \( CH_4 \) are 12,700, 10,800 and 35,000 kJ per cubic metre respectively. What is the gas consumption per kW-hour if the thermal efficiency of engine is 23% ?

Reactions for complete combustion are:

(i) \( 2CO + O_2 = 2CO_2 \)
(ii) \( 2H_2 + O_2 = 2H_2O \)

2 vol. + 1 vol. = 2 vol.
2 vol. + 1 vol. = 2 vol.
1 m³ + ½ m³ = 1 m³
1 m³ + ½ m³ = 1 m³
(iii) \[ CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \]
1 vol. + 2 vol. = 2 vol. + 1 vol.
1 m$^3$ + 2 m$^3$ = 2 m$^3$ + 1 m$^3$

With the help of above equations, oxygen required for complete combustion of 1 cubic metre of producer gas can be calculated as follows:

(i) Volume of $O_2$ required for CO = $0.11 \times \frac{1}{2} = 0.055$ m$^3$,
(ii) Volume of $O_2$ required for $H_2$ = $0.29 \times \frac{1}{2} = 0.145$ m$^3$, and
(iii) Volume of $O_2$ required for $CH_4$ = $0.018 \times 2 = 0.036$ m$^3$

Total oxygen required = 0.236 m$^3$

As air contains 21% oxygen by volume,

Volume of minimum air required for complete combustion of 1 m$^3$ of producer gas

\[ = \frac{0.236 \times \frac{100}{21}}{} = 1.129 \text{ m}^3 \]

As 50% excess air is supplied,

Total air supplied = $1.129 \times 1.5 = 1.694$ m$^3$.

Heat given out by combustion of CO, $H_2$ and $CH_4$

\[ = 0.11 \times 12,700 + 0.29 \times 10,800 + 0.018 \times 35,800 \]

\[ = 1,397 + 3,132 + 644.4 = 5,173.4 \text{ kJ} \]

\[ \therefore \text{Heat supplied by gas per m}^3 = 5,173.4 \text{ kJ} \]

Total mixture (gas and total air supplied) in the cylinder

\[ = 1 + 1.694 \text{ m}^3 = 2.694 \text{ m}^3 \]

Hence, calorific value of the cylinder mixture = \[ \frac{5,173.4}{2.694} = 1,920.3 \text{ kJ/m}^3 \]

As 1 kW = 1 kJ/sec, then one kW-hour = $1 \times 3,600 = 3,600$ kJ.

Thermal efficiency of engine = \[ \frac{\text{Work done in kJ per hr.}}{\text{Heat supplied in kJ per hr.}} \]

\[ = \frac{\text{Work done in kJ equivalent to one kW-hour}}{V_g \text{, gas consumption per kW-hour in m}^3 \times \text{heat supplied in kJ per m}^3 \text{of gas}} \]

\[ \text{i.e. } 0.23 = \frac{3,600}{V_g \times 5,173.4} \]

\[ \therefore V_g = \frac{3,600}{0.23 \times 5,173.4} = 3.025 \text{ m}^3 \]

Hence, gas consumption per kW-hour = 3.025 m$^3$.

**Problem-19**: The fuel supplied to a petrol engine may be assumed to be gasoline having the formula $C_8H_{18}$.

Calculate: (i) the theoretical or minimum air required for complete combustion of 1 kg of fuel, (ii) gross calorific value of fuel per kg, and (iii) the percentage of $CO_2$ in the exhaust, if the fuel is burned with 50% more air than is theoretically required.
In the formation of CO\textsubscript{2}, 1 kg of carbon liberates 33,800 kJ and in the formation of H\textsubscript{2}O, 1 kg of hydrogen liberates 1,44,500 kJ of heat.

(i) The products of combustion will be CO\textsubscript{2} and H\textsubscript{2}O.

Combustion equation of petrol is

\[2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O\]

\[2 \times (12 \times 8 + 1 \times 18) + 25 \times (2 \times 16) = 16 \times (12 + 2 \times 16) + 18 \times (2 \times 1 + 16)\]

\[228 + 800 = 704 + 324\]

Thus, 228 kg of C\textsubscript{8}H\textsubscript{18} require 800 kg of oxygen, for complete combustion.

\[\therefore \text{1 kg of } C_8H_{18} \text{ requires } \frac{800}{228} = 3.5088 \text{ kg of oxygen, and}\]

\[\text{1 kg of } C_8H_{18} \text{ requires } 3.5088 \times \frac{100}{23} = 15.26 \text{ kg of minimum air for complete combustion.}\]

(ii) Heat evolved due to combustion of carbon in 1 kg of petrol

\[= \frac{12 \times 8}{114} \times 33,800 = 28,460 \text{ kJ.}\]

Heat evolved due to combustion of hydrogen in 1 kg of petrol

\[= \frac{18}{114} \times 1,44,500 = 22,820 \text{ kJ}\]

\[\therefore \text{Total heat evolved per kg of petrol} = 28,460 + 22,820 = 51,280 \text{ kJ}\]

Thus, higher calorific value of petrol = 51,280 kJ/kg.

(iii) The exhaust gases produced from 1 kg of petrol are:

\[CO_2 \text{ produced } = \frac{704}{228} = 3.088 \text{ kg,}\]

\[H_2O \text{ produced } = \frac{324}{228} = 1.421 \text{ kg,}\]

N\textsubscript{2} from the actual air supplied = 0.77 \times (15.26 \times 1.5) = 17.625 kg, and

O\textsubscript{2} from the excess air supplied = 0.23 \times (15.26 \times 0.5) = 1.755 kg

Total mass of exhaust gases = 23.889 kg

\[\therefore \% \text{ of } CO_2 \text{ in exhaust gases with 50% excess air } = \frac{3.088}{23.889} \times 100 = 12.93\%\]

7.15 Gas Producer

A gas producer is an apparatus in which inflammable gaseous mixture is produced from solid or liquid fuels. Broadly speaking carburettors, vaporisers, coke oven plants, town's gas plants or blast furnace plants, etc. are all gas producers. However, the term gas producer is applied to an apparatus in which inflammable gaseous mixture is produced in large quantities for power production, heating and other domestic purposes.

Advantages of producing gas from solid fuel are as under:
When coal or other solid fuel is burnt in open fire, considerable waste of fuel and loss of energy occurs and the process of combustion is very inefficient. Gas can be burnt more efficiently and considerable saving of fuel can be effected. This is because the chances for fuel molecules to come in contact with oxygen are more in case of gaseous fuel than that in case of solid or liquid fuel.

Gaseous fuel can be distributed conveniently from a central station for use in number of places.

When gas is produced in a gas producer as a main product, number of by-products are obtained, such as coke, ammonia and tar. Also many tar derivatives such as carbonic acid, naphthalene, dyes, etc. are produced.

Any low quality of fuel containing an excessive amount of ash and moisture such as peat, etc. may be successfully burnt in gas producer to produce gas when their utilisation on steam boiler grate is impossible.

The control of supply of gaseous fuel is easier. This in turn makes temperature control possible and easier.

Producer gas is a name given to a cheaply manufactured type of gas for use in gas engines. It is made by the combustion of any grade of coal with limited supply of oxygen derived from air or mixture of air and steam. Incomplete combustion results in the formation of carbon monoxide. Other constituents of the gas are hydrogen, nitrogen and small percentage of carbon dioxide and oxygen. Producer gas is continuously obtained by passing a current of air mixed with steam in proper proportion through an incandescent (highly heated) bed of fuel. Once the gas producer has started working, no external heat is necessary, as the heat liberated during the process is sufficient for the purpose.

Gas is produced in a gas producer or generator (fig. 7-2). The generator consists of a long cylinder lined with fire bricks throughout and having a grate at the bottom, supporting a deep bed of fuel. The coal is fed from top through a closed hopper; air and steam is drawn through the grate. The hot gases produced pass through an opening near the top of the generator. The gas is then washed, purified and passed into a storage tank from which it is drawn for driving gas engines or for heating purposes. Producer gas has a heating value of 3,770 to 6,490 kJ/m³.

7.15.1 Action of A Gas Producer: Figure 7-2 shows the approximate reactions which take place in the generator and the condition of fuel. The action of gas producer depends upon the depth and temperature of the fuel bed. The bed may be divided into four distinct zones (fig. 7-2) through which the flow of air and steam is maintained by the suction of the engine or by means of a steam blower or injector.
When fresh coal drops on the top of the fuel bed it is heated by the hot gases passing upwards through it, and more volatile gases are immediately given off, leaving carbon (coke) behind. This zone is known as distillation zone. The temperature in this zone is between 370°C and 760°C.

As the hot carbon from distillation zone sinks lower in the generator, it meets the highly heated steam and CO₂ which was formed below in the combustion zone. The result is that CO₂ is reduced to CO by carbon according to reaction, \( CO₂ + C = 2CO \), and steam is decomposed into oxygen and hydrogen. Oxygen combines with carbon forming CO and free hydrogen is added to the gas, according to reaction,

\[
H₂O + C = CO + H₂
\]

Hydrogen, thus, formed may combine with carbon and form \( CH₄ \) or \( C₂H₄ \). This zone is known as reduction zone. The average temperature in this zone is about 980°C.

Lower down in the combustion zone, remaining carbon is burnt to CO₂ according to reaction, \( C + O₂ = CO₂ \) by the incoming air with the production of considerable heat which superheats the steam and raises its temperature above its decomposition temperature. The average temperature in this zone is about 1,100°C.

The lowest zone consists mainly of ash, about 75 cm thick in depth which is sufficient to superheat the steam. This zone is known as ash or neutral zone.

There is, of course, no sharp division line in the generator and the temperature may vary considerably from time to time. The relative amounts of CO and CO₂ ultimately leaving the generator depend largely on the temperature attained in various zones. Higher the temperature, the greater is the amount of CO produced and also a slow velocity of air favours the production of CO.

**7.16 Producer Gas Theory**

The chief reactants in a gas producer which take part in the chemical reaction are \( C, CO, CO₂, H₂O, H₂ \) and \( O₂ \). The amount of heat produced by the burning of one kilogram of carbon to CO is 10,130 kJ, and that when one kilogram of carbon is burnt to CO₂ is 33,830 kJ. One kilogram of hydrogen when burnt to \( H₂O \) gives out 1,21,420 kJ (lower value). If the operations are reversed, that is if \( CO, CO₂ \) and \( H₂O \) are decomposed, then the heat required for their decomposition is the same as the heat given out by their combustion. When carbon is burnt in full supply of air, CO₂ is formed, which cannot be used as a fuel. This will be the case when there is thin fire in the producer and large quantity of air is supplied. The reaction is represented by chemical equation,

\[
C + O₂ = CO₂ + \text{Heat} \quad \text{...(7.5)}
\]

This reaction occurs in actual producer at the bottom of the producer, i.e. in the combustion zone where air enters.

When considerable depth of fuel is used (several centimetres), CO₂ thus formed at the bottom of the producer will be reduced to CO according to the equation,

\[
C + CO₂ = 2CO - \text{Heat} \quad \text{...(7.6)}
\]

This reaction occurs in the gas producer in the reduction zone. Eqn. (7.5) represents burning of carbon to CO₂ and eqn.(7.6) represents subsequent reduction of CO₂ into CO.

CO may also be produced by the direct combustion of carbon with oxygen according to the equation,
COMBUSTION

\[ 2C + O_2 = 2CO + \text{Heat} \]  

...(7.7)

Reactions (7.6) and (7.7) may or probably do occur in an actual generator.

Calorific value of carbon burnt to \( CO \) per kg = 10,130 kJ. Calorific value of carbon burnt to \( CO_2 \) per kg = 33,830 kJ. Thus, the percentage heat available in \( CO \) gas per kg of carbon and evolved by burning to \( CO_2 \) is \[ \frac{33,830 - 10,130}{33,830} \times 100 \] i.e. about 70% of the total heat obtained by completely burning the solid carbon. This means that if there are no heat losses, the efficiency of the producer will be about 70%. The remaining 30% of the total heat is wasted in preparing the combustible gas. This is in a way not permissible.

The 30% (i.e. 10,130 kJ per kg) of the total heat of carbon need not, however, be entirely lost. Out of this, about 8% is lost in radiation and conduction, and a large proportion will be carried away with gas as sensible heat, and the gas produced will be at a high temperature. The high temperature obtained in the producer may be excessive and may cause trouble in the working of the producer by the formation of clinker, which may cause serious trouble by blocking the air passages. To avoid the production of too high a temperature and to raise the theoretical efficiency of the producer to 100% (i.e. to reduce 30% loss), some of the sensible heat may be used to generate steam to be added to the air blast. By the mixing of steam with air and passing it through the producer, heat is absorbed in the decomposition of the steam, the oxygen of steam combines with carbon and free hydrogen is added to the gas, while temperature of the producer is under control. (heat absorbed to decompose steam is 1,21,420 kJ per kg of steam). The gas is enriched, both by the presence of hydrogen and reduction in the amount of nitrogen.

Steam may react on the carbon in the following ways:

\[ C + H_2O = CO + H_2 - \text{Heat} \]  

...(7.8)

\[ C + 2H_2O = CO_2 + 2H_2 - \text{Heat} \]  

...(7.9)

Both these reactions cause a large absorption of heat. At temperature above 1,000°C, reaction represented by eqn. (7.8) is more likely to occur but at temperature of about 600°C and under, reaction represented by eqn. (7.9) takes place; while at temperature between 600°C and 1,000°C, the two reactions take place simultaneously. It is evident that since eqn. (7.8) gives rich gas and greater absorption of heat, the best results will be obtained in practice when working at the highest temperature consistent with practical considerations.

The proportion of water which should be used to obtain gas of the highest calorific value can be determined theoretically as shown below, but this in practice is largely
affected by the nature and composition of fuel used and the size of the producer (generator). The mass of water varies from 0.5 kg for large producers to 0.7 kg for small producer per kg of coal gassified.

The richest gas and maximum efficiency will be obtained by the ideal reactions given below;

\[ 2C + O_2 = 2CO + \text{Heat (primary reaction), and} \]
\[ C + H_2O = CO + H_2 - \text{Heat (secondary reaction)} \]

The arrangement is represented by diagrammatic sketch in fig. 7-3. Assume no heat loss by radiation and all sensible heat of gases leaving the producer is utilised in the reactions, so that all the heat energy of the fuel is available. Then, the amount of heat absorbed by the interaction of steam and carbon will be equal to heat evolved (developed) by the formation of CO from carbon with oxygen in the air.

Let the primary reaction be denoted by (a) and the secondary by (b). Then,

(a) \[ 2C + O_2 = 2CO + \text{Heat} \]
\[ \text{i.e. } 24 \text{ kg } C + 32 \text{ kg } O_2 = 56 \text{ kg } CO + 24 \times 10,130 \text{ kJ heat} \]
\[ = 56 \text{ kg } CO + 2,43,120 \text{ kJ heat} \]

(b) \[ C + H_2O = CO + H_2 + \text{heat} \]
\[ \text{i.e. } 12 \text{ kg } C + 18 \text{ kg } H_2O = 28 \text{ kg } CO + 2 \text{ kg } H_2 + (1,21,420 - 2,43,120) \text{ kJ heat} \]
\[ = 28 \text{ kg } CO + 2 \text{ kg } H_2 - 1,21,700 \text{ kJ heat} \]

which shows that the addition of 18 kg of steam to 12 kg of carbon absorbs 2,43,120 kJ to decompose the steam and produces 1,21,420 kJ by the combustion of carbon to CO; the net result of the double reaction being the absorption of 2,43,120 - 1,21,420 = 1,21,700 kJ from the generator.

\( H_2O \) is supplied to the producer as water and not as steam. If the water enters the generator at 18°C and is evaporated into steam at 100°C, then the heat absorbed per kg of water = 4.187 (100 - 18) + 2,257 = 2,590 kJ.

From reaction (b) it will be seen that, 1,21,700 kJ are absorbed when 18 kg of steam is decomposed by 12 kg of carbon. In addition to the heat absorbed directly from the furnace by 18 kg of steam during decomposition, there is, heat required to produce this steam from water before it enters the furnace. This heat is provided by the hot gases leaving the generator and therefore, comes from the heat available in the fuel. The amount of heat absorbed from the furnace in producing 18 kg of steam is 18 x 2,590 = 46,620 kJ. Therefore, the total heat absorbed from the furnace in producing and decomposing 18 kg of steam in the secondary reaction is 1,21,700 + 46,620 = 1,68,320 kJ heat,

\[ \text{i.e. } 12 \text{ kg } C + 18 \text{ kg } H_2O = 28 \text{ kg } CO + 2 \text{ kg } H_2 - 1,68,320 \text{ kJ heat}. \]

In order to obtain heat balance or thermal equilibrium between the primary and secondary reactions, reaction (b) must be multiplied by the ratio \( \frac{2,43,120}{1,68,320} \) i.e. by 1.444 throughout.

The reaction (b) becomes \[ 12 \times 1.444 \text{ kg } C + 18 \times 1.444 \text{ kg } H_2O \]
\[ = 28 \times 1.444 \text{ kg } CO + 2 \times 1.444 \text{ kg } H_2 - 1,68,320 \times 1.444 \text{ kJ heat} \]
i.e. 17.328 kg C + 25.992 kg H₂O absorb 2,43,120 kJ
and from reaction (a) 24 kg C + 32 kg O₂ liberate 2,43,120 kJ
Total carbon used = 17.328 + 24 = 41.328 kg
Total steam (H₂O) used = 25.992 kg
Total oxygen used = 32 kg.

1 kg of carbon needs \( \frac{25.992}{41.328} = 0.629 \) kg of H₂O (water)
and 1 kg of carbon needs \( \frac{32}{41.328} = 0.774 \) kg of O₂ (oxygen)

= 0.774 \times \frac{100}{23.1} \) kg of air = 3.352 kg of air.

7.17 Types of Gas Producers

There are two main types of gas producers. These are:
— Suction gas producer which works under a slight vacuum, and
— Pressure gas producer which works under a slight gauge pressure.
Both types may be designed to work with bituminous or non-bituminous coal.

In suction gas producer which is illustrated in fig. 7-4, mixture of air and steam
is drawn through the fuel bed due to suction created by the piston of gas engine
during its charging (suction) stroke. The interior of the producer is kept at a pressure
less than atmospheric pressure. The producer consists of a cylindrical shell of mild steel
or cast iron. It is lined throughout with the fire bricks. An annular space is provided
between the fire bricks and the casing for the passage of steam and air which is
thereby preheated, and the loss from radiation is reduced in consequence.

On the top of the generator, a coal charging hopper is provided to admit fresh
coal to the fuel bed of the producer without interfering with the operation of the producer.
A conical bell makes a gas tight seal between the hopper and generator. A number
of holes are arranged around the top of the generator for the insertion of poker (a
metal rod). Taper plugs are inserted in these holes to prevent air entering the generator.

A starting blower is used for starting the producer, and during the starting period
the products of combustion are blown to waste by opening the starting cock.

The hot gases leaving the generator are utilised in evaporating the water in the
steam boiler (fig. 7-4). No external boiler for generating steam is, therefore, required. At
the base of the generator, a fire grate, a hand hole for removing ash, and a valve
for controlling the supply of steam and air are provided.

The hot gases which are still hot for use in gas engine and contain dust and
little tar, pass to the coke scrubber. The coke scrubber is vertical steel cylinder containing
pieces of coke (about 8 cm in size), over which water is continuously falling from a
spraying arrangement on the top of the scrubber. The gas is cooled and cleaned on
passing through the scrubber.

In addition to coke scrubber, a saw dust scrubber (not shown in fig. 7-4) is provided
through which the gas finally passes, so as to remove the last trace of the dust and
moisture present in the gas. The arrows in fig. 7-4 show the path of the gas.
To operate the plant, a small quantity of firewood and coal sprinkled with kerosene is dropped on the hearth (fuel bed) through the hopper. The starting cock (fig. 7-4) is opened and the steam boiler is filled with water. The starting blower is worked and after about 20 minutes the fire is sufficient to give off gas. The starting cock is then closed and the formation of gas becomes automatic, the suction of the engine furnishing the draught through the fire. The gas coming out is tested at a small test cock until it comes out with orange red flame. Water spray in the coke scrubber must be turned on as soon as the gas begins to pass through the scrubber. The spray of water should be sufficient to keep the coke scrubber vessel cool.

The suction gas producers is largely used where power only is required (i.e. for driving gas engines).

Pressure Gas Producer shown in Fig. 7-5 is a Downson pressure gas producer for use with non-bituminous coal or coke. The gas producer using non-bituminous coal is chiefly adopted for those plants which require gas for combined power and heating purposes or heating purpose only. For heating purposes the gas must be supplied at a steady pressure and should be of uniform quality to prevent the gas jets being extinguished. A gas holder is, therefore, valuable with pressure gas producer.

In this producer (fig. 7-5), there is small, separately fired, vertical steam boiler for producing steam. The steam produced is used in an injector for drawing in supply of air, and forcing mixture of steam and air through the grate. On the top of the generator, a coal charging hopper is provided to admit fresh coal to the fuel bed.

The products of combustion (gas) from the generator are conveyed through a pipe into a coke scrubber filled with coke, over which water is continuously falling through a spraying arrangement at the top of the coke scrubber. The function of coke scrubber is to cool and partly clean the hot smoky gas issuing from the producer. The tar and dust laden water from the coke scrubber runs away through a simple water seal as
shown in fig. 7-5.

As in the case of suction gas producer, in addition to the coke scrubber, a saw dust scrubber is provided through which the gas passes, so as to remove the last trace of the dust and moisture.

This clean and cooled gas is then taken through the gas valve into the gas holder from which it is drawn for use. The gas holder is used for supplying gas at steady pressure and of uniform quality, and for storing gas. The arrows in fig. 7-5 show the path of the gas. For the operation of plant refer suction gas producer.

**Problem-20**: A gas producer is supplied with fuel containing 93 per cent carbon and 7 per cent ash on mass basis. The reactions are such that gas given out from the producer consists solely of carbon monoxide, hydrogen and nitrogen. Determine the percentage volumetric analysis of the producer gas; also determine, the mass of water and mass of air needed per kilogram of fuel burnt.

Assume that the calorific value of carbon burnt to carbon monoxide is 10,260 kJ/kg; that the L.C.V. of hydrogen is 1,23,520 kJ/kg; that the heat required to generate one kilogram of steam from water supplied is 2,610 kJ; that all heat losses are negligible.

Air contains 23.1 per cent oxygen on mass basis.

(a) \[ 2C + O_2 \rightarrow 2CO + \text{heat} \text{ (primary reaction)} \]

i.e. \[ 24 \text{ kg} \ C + 32 \text{ kg} \ O_2 \rightarrow 56 \text{ kg} \ CO + 24 \times 10,260 \text{ kJ} \]

\[ \rightarrow 56 \text{ kg} \ CO + 246,240 \text{ kJ} \]

(b) \[ C + H_2O \rightarrow CO + H_2 \text{ - Heat} \text{ (secondary reaction)} \]

i.e. \[ 12 \text{ kg} \ C + 18 \text{ kg} \ H_2O \rightarrow 28 \text{ kg} \ CO + 2 \text{ kg} \ H_2 \text{ - Heat} \]

The heat required for dissociation of steam to form 1 kg of H\(_2\) is given as 1,23,520 kJ. 1 kg of steam requires 2,610 kJ for its generation.

18 kg of \( H_2O \) is evaporated and absorb \( 18 \times 2,610 = 46,980 \text{ kJ} \).

18 kg of \( H_2O \) is dissociated into 2 kg of hydrogen and absorb \( 2 \times 1,23,520 = 2,47,040 \text{ kJ} \).
12 kg of carbon combine with 16 kg of \( O_2 \) and liberate \( 12 \times 10,260 = 1,23,120 \) kJ.

:. Net, absorption of heat in secondary reaction

\[
= 2,47,040 + 46,980 - 1,23,120 = 1,70,900 \text{ kJ}
\]

i.e. 12 kg of \( C \) + 18 kg of \( H_2O \) \( \rightarrow \) - 1,70,900 kJ ..(ii)

In order to obtain heat balance between the primary and secondary reactions, secondary reaction \( \text{(ii)} \) should be multiplied throughout by the ratio \( \frac{2,46,240}{1,70,900} \), i.e. by 1.441 throughout

i.e. 17.29 kg of \( C \) + 25.94 kg of \( H_2O \) \( \rightarrow \) absorb 2,46,240 kJ

and from \( \text{(a)} \) 24 kg of \( C \) + 32 kg of \( O_2 \) \( \rightarrow \) liberate 2,46,240 kJ

:. 41.29 kg of \( C \) will need 25.94 kg of \( H_2O \).

:. 1 kg of \( C \) will need \( \frac{25.94}{41.29} = 0.628 \) kg of \( H_2O \).

and \( 0.628 \times 0.93 = 0.584 \) kg of \( H_2O \) per kg of fuel.

Again 41.29 kg of \( C \) will need 32 kg of \( O_2 \).

:. 1 kg of \( C \) will need \( \frac{32}{41.29} = 0.775 \) kg of \( O_2 \).

and \( 0.775 \times 0.93 \times \frac{100}{23.1} = 3.12 \) kg of air per kg of fuel.

The products are:

\[
\begin{align*}
\text{CO, } 56 + 28 \left( \frac{2,46,240}{1,70,900} \right) & = 56 + 40.35 = 96.35 \text{ kg, i.e. } \frac{96.35}{28} = 3.441 \text{ mols.} \\
\text{H}_2, 2 \left( \frac{2,46,240}{1,70,900} \right) & = 2.882 \text{ kg, i.e. } \frac{2.882}{2} = 1.441 \text{ mols.} \\
\text{N}_2, 76.9 \times 32 & = 106.53 \text{ kg, i.e. } \frac{106.53}{28} = 3.804 \text{ mols.}
\end{align*}
\]

Total products = 3.441 + 1.441 + 3.804 = 8.686 mols.

Volumetric analysis of \( \text{producer gas by percentage} \)

\[
\begin{align*}
\text{CO, } & 3.441 \\
\text{H}_2, & 1.441 \\
\text{N}_2, & 3.804
\end{align*}
\]

\[
\begin{align*}
\times 100 \text{ = } 39.62\% \\
\times 100 \text{ = } 16.59\% \\
\times 100 \text{ = } 43.79\% \\
\Sigma = 100.00\%
\end{align*}
\]

Volumetric analysis of producer gas is

\[
\begin{align*}
\text{CO} & = 39.62\%; \quad \text{H}_2 = 16.59\%; \quad \text{N}_2 = 43.79\%.
\end{align*}
\]

Problem-21: Calculate the mass of air and steam which should be supplied per kg of carbon in a suction gas plant assuming that no \( \text{CO}_2 \) is formed. Calorific value of hydrogen is 1,42,360 kJ/kg and one kilogram of carbon burned to \( \text{CO} \) gives 10,130 kJ. Also calculate the percentage volumetric analysis of the producer gas produced. Air contains 23% oxygen on mass basis.
In the production of the gas following two reactions take place:

(a) \[2\text{C} + \text{O}_2 = 2\text{CO} + 24 \times 10,130 \text{kJ}\]

\[24 \text{kg} + 32 \text{kg} = 56 \text{kg} + 24 \times 10,130 \text{kJ}\]

i.e. \[1 \text{kg} + 1 \frac{1}{3} \text{kg} = 2 \frac{1}{3} \text{kg} + 10,130 \text{kJ}\]

1 kg of C + 4\frac{1}{3} \text{kg of O}_2 = 7\frac{1}{3} \text{kg CO} + 10,130 \text{kJ} 

..(i)

(b) \[\text{C} + \text{H}_2\text{O} = \text{CO} + \text{H}_2 - \text{Heat}\]

\[12 \text{kg} + 18 \text{kg} = 28 \text{kg} + 2 \text{kg} - \text{Heat}\]

i.e. \[1 \text{kg} + 11\frac{1}{2} \text{kg} = 2\frac{1}{2} \text{kg} + \left[10,130 - \frac{1}{6} (1,42,360) \text{kJ}\right]\]

(\because 1 \text{kg of C burning to CO produces } 10,130 \text{kJ, and } 1 \text{kg of H}_2 \text{liberated from steam requires } 1,42,360 \text{kJ}).

Hence, we have,

1 kg of C + \frac{3}{2} \text{kg of H}_2\text{O} = 7\frac{1}{3} \text{kg CO} + \frac{1}{6} \text{kg H}_2 \text{produces } 10,130 \text{kJ and absorbs}\]

\[\frac{1}{6} \times 1,42,360 \text{kJ}\]

\[= 7\frac{1}{3} \text{kg CO} + \frac{1}{6} \text{kg H}_2 + 10,130 - \frac{1}{6} \times 1,42,360\]

\[= 7\frac{1}{3} \text{kg CO} + \frac{1}{6} \text{kg H}_2 - 13,596 \text{kJ} \quad \text{..(iia)}\]

It follows that for reaction (iia) to be brought about, sufficient carbon must be burnt in reaction (i) to supply 13,596 \text{kJ}. Hence to obtain a heat balance between two reactions, we must multiply reaction (iia) by the ratio \[\frac{10,130}{13,596}\]

Thus, we get,

\[\frac{10,130}{13,596} \left[1 \text{kg C} + \frac{3}{2} \text{kg H}_2\text{O}\right]\]

\[= \frac{10,130}{13,596} \left[7\frac{1}{3} \text{kg CO} + \frac{1}{6} \text{kg H}_2 - 13,596 \right] \text{kJ}\]

or \[0.745 \text{ kg C} + 1.12 \text{ kg H}_2\text{O} = 1.74 \text{ kg CO} + 0.124 \text{ kg H}_2 - 10,130 \text{kJ} \quad \text{..(ii b)}\]

The heat required for reaction (ii b) is now equal to the heat liberated in reaction (i).

Total carbon required per kg of C burnt to CO = 1 + 0.745 kg = 1.745 kg.

Total \text{O}_2 \text{required per kg of C burnt in both reactions} = \frac{1.333}{1.745} = 0.765 \text{ kg}.

Mass of air required per kg of C burnt = 0.765 \times \frac{100}{23} = 3.32 \text{ kg}

Mass of steam required per kg of C burnt = \frac{1.12}{1.745} = 0.642 \text{ kg}

The two reactions yield, 1.74 + 2.33 = 4.07 kg of CO; 0.124 kg of H\text{, and} \frac{1.333 \times 77}{23} = 4.453 \text{ kg of N}_2.

From this % composition on mass basis = CO, 47.07%; H\text{, 1.434; and N}_2, 51.496
Conversion to percentage analysis by volume of producer gas:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>% by mass + molecular weight</th>
<th>% composition by volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>47.07 + 28 = 1.681</td>
<td>( \frac{1.681}{4.238} \times 100 = 39.67 )</td>
</tr>
<tr>
<td>H₂</td>
<td>1.434 + 2 = 0.717</td>
<td>( \frac{0.717}{4.238} \times 100 = 16.92 )</td>
</tr>
<tr>
<td>N₂</td>
<td>51.496 + 28 = 1.84</td>
<td>( \frac{1.84}{4.238} \times 100 = 43.41 )</td>
</tr>
<tr>
<td>Total</td>
<td>= 4.238</td>
<td>= 100.00</td>
</tr>
</tbody>
</table>

Volumetric analysis of producer gas is,

\( CO = 39.67\%; \quad H₂ = 16.92\%; \quad N₂ = 43.41\% \)

**Tutorial-7**

1. What do you understand by combustion? Explain the terms “minimum mass of air” and “excess air” with reference to combustion of fuel.

2. Determine from first principles the minimum quantity of air required for complete combustion of 1 kg of (i) carbon \((C)\), (ii) hydrogen \((H)\), and (iii) methane gas \((CH₄)\).

   \[(i) 11.6 \text{ kg}; \quad (ii) 34.78 \text{ kg}; \quad (iii) 17.39 \text{ kg} \]

3. Prove that minimum air required for complete combustion of one kg fuel having \(C\) kg of carbon, \(H\) kg of hydrogen, \(S\) kg sulphur and \(O\) kg oxygen in one kg fuel is given by \( \frac{100}{23} (2.67C + 8H + S - O) \) kg

4. The percentage composition of a fuel oil on mass basis is as follows:
   
   \( C, 85.1; \quad H₂, 13.7; \quad \text{and} \quad O₂, 1.2 \)

   Calculate, the minimum air required to burn completely 1 kg of this fuel oil and hence the percentage composition of the dry products of combustion on mass and volume basis.

   \[14.55 \text{ kg}; \quad \text{percentage composition by mass} - \ CO₂, 21.8; \quad N₂, 78.2; \quad \text{percentage composition by volume} - \ CO₂, 15.1; \quad N₂, 84.9 \]

5. The percentage composition of coal on mass basis is given as:

   \( C, 90; \quad H₂, 3.5; \quad O₂, 1; \quad S, 0.5; \quad \text{and ash, 5.} \)

   Calculate: (a) the minimum air required for the complete combustion of 1 kg of this coal, and (b) the composition of dry flue gases on mass basis if 50% excess air is supplied.

   \[(a) 11.6 \text{ kg}; \quad (b) \text{composition by mass} - \ CO₂, 18.253\%; \quad O₂, 7.4\%; \quad SO₂, 0.055\%; \quad N₂, 74.292\% \]

6. A certain coal has following percentage composition on mass basis: \(C, 0.8; \quad H₂, 0.1; \quad \text{and} \quad S, 0.1\). The analysis of the flue gases shows the following composition by volume:

   \( CO₂, 10\%; \quad CO, 1\%; \quad O₂, 10\%; \quad \text{and} \quad N₂, 79\% \).

   Find, (a) the minimum air required per kg of coal, (b) the air actually supplied per kg of coal, and (c) the excess air supplied per kg of coal.

   \[(a) 13.18 \text{ kg}; \quad (b) 17.36 \text{ kg}; \quad (c) 4.18 \text{ kg} \]

7. In a boiler trial, the percentage composition of coal on mass basis was reported as:

   \( C, 88; \quad H₂, 3.6; \quad O₂, 4.8; \quad \text{and ash, 3.6.} \)

   The percentage composition of dry flue gases by volume was reported as:

   \( CO₂, 10.9; \quad CO, 1; \quad O₂, 7.1; \quad \text{and} \quad N₂, 81 \)

   Find, (a) the mass of air actually supplied per kg of coal, and (b) the percentage of excess air supplied.

   \[(a) 18.15 \text{ kg}; \quad (b) 38.3\% \]
8. In a boiler trial, the sample of coal fired, contained carbon 88% by mass and the ash in it was 3.6%. The volumetric analysis of the gases gave the following percentages:

\[
\begin{align*}
& \text{CO}_2, 10.9; \text{CO}, 1; \text{O}_2, 7.1; \text{and} \ N_2, 81
\end{align*}
\]

Find, (a) the proportion of carbon burned to CO, (b) the air required per kg of coal for the combustion as it actually occurred, and (c) the mass of dry flue gases formed per kg of coal burned.

(a) 8.4%; (b) 18.15 kg; (c) 19.114 kg

9. The percentage composition of a sample of coal on mass basis is as follows:

\[
\begin{align*}
& \text{C}, 82; \text{H}_2, 6; \text{O}_2, 4; \text{ash}, 6; \text{and moisture}, 2.
\end{align*}
\]

Determine the theoretical or minimum air required for complete combustion of 1 kg of coal.

If the actual air supply is 18 kg per kg of coal, the hydrogen is completely burned, and 80% of carbon contained in 1 kg of coal is completely burned to \( \text{CO}_2 \) and the remainder is burned to CO, calculate the percentage composition by volume of the dry flue gases. (Air contains 23% \( \text{O}_2 \) on mass basis).

[11.5 kg; percentage composition by volume \( \text{CO}_2, 8.84; \text{CO}, 2.25; \text{O}_2, 8.76; \ N_2, 80.15 \)]

10. A fuel oil has the following analysis on mass basis:

\[
\begin{align*}
& \text{C}, 85\%; \text{H}_2, 4; \text{O}_2, 5; \text{S}, 1; \text{moisture}, 2; \text{and ash}, 6.
\end{align*}
\]

Determine the air-fuel ratio.

21.25 : 1

11. Describe the Orsat apparatus for the analysis of the dry flue gases from a boiler and briefly describe the procedure for carrying out the experiment.

12. The percentage dry flue gas analysis by volume in a boiler trial was: \( \text{CO}_2, 12; \text{CO}, 1; \text{O}_2, 7; \text{and} \ N_2, 80 \). The percentage analysis of the coal on mass basis was: \( \text{C}, 82; \text{H}_2, 4; \text{O}_2, 5; \text{S}, 1; \text{moisture}, 2; \text{and ash}, 6 \).

Determine: (a) the total mass of flue gases per kg of fuel burnt, (b) the mass of excess air supplied per kg of fuel burnt, and (c) the heat carried away by the products of combustion leaving the boiler per kg of fuel burnt, if the average specific heat of the dry flue gases is 1.005 kJ/kg K and the temperature of the flue gases is 325°C and the boiler house temperature is 25°C. Assume steam to be at atmospheric pressure and specific heat of superheated steam as 2.1 kJ/kg K.

(a) 16.28 kg; (b) 4.62 kg; (c) by dry flue gases, 4,793.85 kJ, by steam, 1,156.7, total heat, 5,950.55 kJ

13. Estimate the minimum volume of air required for complete combustion of 1 m³ of fuel gas having the following volumetric analysis:

\[
\begin{align*}
& \text{CH}_4, 39.5%; \text{H}_2, 46%; \text{N}_2, 0.5%; \text{CO}, 7.5%; \text{H}_2\text{O}, 2%; \text{and CO}_2, 4.5%.
\end{align*}
\]

Air contains 21% \( \text{O}_2 \) by volume.

[5.04 m³]

14. A fuel gas has the following percentage composition by volume:

\[
\begin{align*}
& \text{CO}, 30; \text{CH}_4, 5; \text{H}_2, 10; \text{and} \ N_2, 55.
\end{align*}
\]

Calculate: (a) the minimum volume of air required for the complete combustion of 1 m³ of this gas, and (b) the percentage composition by volume of the dry products of combustion. (Air contains 21% \( \text{O}_2 \) by volume).

[(a) 1.429 m³; (b) percentage composition by volume - \( \text{CO}_2, 17.25; \ N_2, 82.75 \)]

15. A fuel gas has the following composition by volume:

\[
\text{H}_2, 20%; \text{CH}_4, 2%; \text{CO}, 24%; \text{CO}_2, 6%; \text{O}_2, 3%; \text{and} \ N_2, 45%.
\]

If 25% excess air is supplied, calculate the mass of air at 0°C and 1.01325 bar (N.T.P) actually supplied for the combustion of 1 m³ of this gas and also the percentage composition by volume of dry flue gases. Take the specific volume of air at 0°C and 1.01325 bar as 0.7734 m³/kg. (% composition of air by volume: \( \text{N}_2, 79; \text{O}_2, 21 \)).

[1.785 kg; percentage composition by volume - \( \text{CO}_2, 16.74; \ N_2, 80.26; \text{O}_2, 3 \)]

16. The fuel supplied to a petrol engine may be assumed to have the formula \( \text{C}_7\text{H}_{16} \).

Calculate: (i) the minimum air required for complete combustion of 1 kg of fuel, (ii) the gross calorific value of fuel per kg; and (iii) the percentage of \( \text{CO}_2 \) in the exhaust gases, if the fuel is burned with 30% excess air.

Assume that 1 kg of carbon liberates 33,800 kJ forming \( \text{CO}_2 \) and 1 kg of hydrogen liberates 1,44,450 kJ forming \( \text{H}_2\text{O} \).

[(i) 15.3 kg; (ii) 51,504 kJ; (iii) 14.73%]
17. A producer gas used by a gas engine has the following percentage composition by volume:

\[ CO = 15; \ H_2 = 25; \ CH_4 = 2; \ CO_2 = 12; \text{ and } N_2 = 46. \]

Calculate the volume of minimum air required to completely burn one cubic meter of producer gas.

If the air supplied to the engine is 40% in excess, what is the calorific value of one cubic metre of cylinder mixture? Calorific values of CO, H\(_2\) and CH\(_4\) are 12,560, 10,890 and 35,600 kJ per cubic metre respectively. What is the gas consumption per kW-hour, if the engine thermal efficiency is 24 percent?

\[ 1.143 \text{ m}^3; \ 2,206 \text{ kJ/m}^3; \ 2,615 \text{ m}^3 \]

18. What is meant by the term “Gas producer”. Explain in detail the advantages of producing gaseous fuel from solid and liquid fuels.

19. Differentiate between “Suction gas producer” and “Pressure gas producer”. Explain their working in brief.

20. Explain with the help of sketches, the construction and working of any one type of gas producer suitable for running a small gas engine.

A suction gas producer is supplied with fuel containing 94% carbon and 6% ash on mass basis. The reactions are such that the producer gas from the gas producer consists of hydrogen, carbon monoxide and nitrogen only.

Determine: (i) the mass of steam and air required per kilogram of fuel burnt, and (ii) the percentage volumetric analysis of the producer gas. Neglect all heat exchanges except those in the chemical reactions.

Assume that the calorific value of carbon burnt to carbon monoxide is 10,130 kJ/kg, the L.C.V. of hydrogen is 1,21,420 kJ/kg; heat given to steam is 2,610 kJ/kg and air contains 23.1% O\(_2\) on mass basis and 21% O\(_2\) on volume basis.

\[ (i) \ 0.5912 \text{ kg of steam/kg of fuel; } 3.154 \text{ kg of air/kg of fuel}; \]

\[ (ii) \ CO, 39.62%; \ H_2 16.65%; \ N_2, 43.775\% \]

21. Give a short account of the reactions which may take place in a suction gas producer supplied with carbon, air and steam. What are the advantages of adding steam with air?

Carbon in the form of coke with 12% ash, is used as a fuel in gas producer. Water is supplied at 15°C and the resulting reactions of both the water and the air with carbon produce CO, there being no CO\(_2\) in the gas produced. The generation of the steam and its subsequent dissociation together absorb 94% of the heat liberated by the partial combustion of carbon with the air. The gross or higher calorific value of hydrogen is 1,44,450 kJ/kg and the heat produced by burning 1 kg of carbon to carbon monoxide is 10,360 kJ/kg.

Air contains 23% oxygen on mass basis and temperature of the gas may be neglected. Estimate: (i) the mass of air and water required per kg of coke, and (ii) percentage volumetric analysis of the gas produced.

\[ (i) \ 2.96 \text{ kg of air and 0.5478 kg of water per kg of coke; } \]

\[ (ii) \ CO, 39.55%; \ H_2, 16.42; \ N_2, 44.03\% \]

22. Make a diagrammatic sketch of any one type of gas producer and explain its working. Give chemical reactions involved in the process of manufacture of producer gas.

23. What is meant by the term “Producer gas”? Draw a layout plan of a suction gas producer gas plant incorporating therein a device to measure the quantity of gas produced. State the functions of various zones and chemical reactions involved in each one of these zones.

24. Sketch a typical form of gas producer using steam blast, and describe briefly the reactions that occur therein.