Chemical Engineering

Process Calculations

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

MADE EASY
Publications

Process Calculations

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Contents

Process Calculations

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Combustion

LEARNING OBJECTIVES

The reading of this chapter will enable the students

• To understand the fuel and its types.

• To understand the concept of caloric values of fuels.

• To understand about theoretical air and excess air.

4.1 Introduction

• Combustion, or burning, is a high-temperature exothermic redox chemical reaction between a fuel and an oxidant, usually atmospheric oxygen, that produces oxidized, often gaseous products, in a mixture termed as smoke.

• Combustion is a unit operation.

• Combustion is a process in which oxidation reaction occur.

• Combustion is called complete combustion when combustion product of carbon, hydrogen and sulphur are carbon dioxide, water and sulphur dioxide.

• Combustion is called incomplete if carbon monoxide appears in product gases, because carbon monoxide further react with oxygen to give CO_2.

4.2 Types of Fuels

Some of the more common fuels are :

1. **Solid Fuels :** Principally coal which is a mixture of carbon, hydrogen, non-combustible ash, water and sulphur, coke and to some extent wood, bagasse.

2. **Liquid Fuels :** Principally hydrocarbons obtained by distillation of a crude oil (petroleum).

3. **Gaseous Fuels :** Principally natural gas which usually contains 80 to 95% methane, the balance being ethane, propane and small quantities of other gases, light hydrocarbons, acetylene, etc.

The rapid reaction of a fuel with oxygen is known as combustion. In combustion operation, the union of carbon, hydrogen and sulphur of fuel takes place with oxygen. When a fuel is burned, the carbon in the fuel reacts to form either CO_2 or CO, hydrogen reacts to form H_2O and sulphur reacts to form SO_2. The combustion is

termed as complete combustion if the products of combustion are CO_2, H_2O and SO_2. A combustion reaction in which CO is formed is referred to as partial or incomplete combustion. Examples :

$C + O_2 \rightarrow CO_2$ complete combustion of carbon.

$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$ complete combustion of propane.

$C_3H_8 + \dfrac{7}{8} O_2 \rightarrow 3CO + 4H_2O$ partial combustion of propane.

4.3 Calorific Values of Fuels

1. When a unit mass of fuel is completely burnt with pure oxygen then total heat produced is called calorific or heating value.

2. The calorific value of a fuel is negative of heat of combustion of fuel.

3. When a fuel is burnt, during burning hydrogen combines with oxygen and gets converted into water (H_2O). If water vapour present in the flue gases, then latent heat of vaporization is lost.
    *   Hence this quantity of heat is not available for any useful purpose.
    *   So when fuel calorific value is determined by considering that the water in vapour form is present then it is called **net calorific value (NCV)**.

    $$NCV = GCV - m\lambda$$

    Where GCV = Gross calorific value, m = weight of water vapour, λ = Latent heat of vaporization of water.

4. NCV is also given by

    $$NCV = GCV - \frac{\text{weight \% of } H_2 \times 9 \times \lambda}{100}$$

5. NCV (net calorific value) is also called net heating value or lower heating value.

6. If the water vapour is condensed, then the sum of water vapour latent heat and net calorific value is called **gross calorific value** (GCV).

7. GCV (gross calorific value) is also called gross heating value or higher heating value.

8. Generally, NCV and GCV of fuels are reported at 25° C (reference temperature).

9. When calorific value is reported then it is needed to specify NCV or GCV. If nothing is mentioned then we can assume calorific value as GCV.

10. In calorimeter we determine fuel's calorific value.

11. In calorimeter fuel is burnt with pure oxygen and then heat released is absorbed in water. The increase in water temperture can be used to calculate fuel's calorific value.

12. Two calorific value (NCV & GCV) are related by following equation

    $$NCV = GCV - (\text{Weight fraction of } H_2) \times 9 \times \lambda \text{ kJ/kg}$$

    where $\qquad\qquad \lambda = $ latent heat of vaporization

13. The most important solid fuel is coal.

14. The ultimate analysis and proximate analysis of coals are reported.
    (i)   Proximate analysis of air dried coal includes moisture content, volatile matter content, fixed carbon and mineral matter content.
    (ii) The ultimate analysis of fuel is correlated with its calorific value.

(iii) The ultimate analysis of coal give the various elemental percentage, (such as carbon, hydrogen, sulphur, nitrogen and oxygen).

4.4 Air Requirement

For any combustion process, i.e., for the chemical oxidation of a fuel, oxygen is a must which will combine with carbon, hydrogen and sulphur. In normal practice, air is used for burning a fuel as it being an inexpensive source of oxygen. Air contains about 21% oxygen and 79% nitrogen by volume. It is normal practice to feed a less expensive reactant in excess of a valuable one to increase the conversion of the valuable reactant. Hence, combustion reactions are invariably run with more air than needed to supply oxygen in the stoichiometric proportion to the fuel.

4.4.1 Theoretical Oxygen

It is the amount of oxygen needed for complete combustion of all the fuel fed to the combustion chamber, assuming that all carbon in the fuel reacts with oxygen to form CO_2, all hydrogen reacts to form H_2O and all sulphur reacts to form SO_2.

4.4.2 Theoretical Air

It is the quantity of air that contains the theoretical oxygen, i.e., it is the minimum air required to burn the fuel completely so that all carbon gets converted into CO_2, all hydrogen into H_2O and all sulphur into SO_2.

Theoretical air requirement of any fuel is calculated as

$$\text{Theoretical air requirement in moles} = \frac{\text{Theoretical oxygen requirement in moles}}{0.21} \qquad ...(4.1)$$

In actual combustion practice, air is used in excess of that theoretically required to assure complete combustion.

4.4.3 Excess Air

It is the amount by which the air fed to the combustion chamber exceeds the theoretical air.

$$\text{Percent excess air} = \left(\frac{\text{actual air supply} - \text{theoretical air requirement}}{\text{theoretical air requirement}} \right) \times 100$$

$$...(4.2)$$

$$\% \text{ excess oxygen} = \% \text{ excess air}$$

The quantities of actual air supplied and theoretical air required can be used either in weight units or in molar units in equation (4.2).

The actual air supply is obtained knowing the % excess and theoretical air requirement by the realtion:

$$\text{Actual air supply} = \text{Theoretical air requirement}\left[1 + \frac{\% \text{ excess}}{100}\right] \qquad ...(4.3)$$

The excess air requirement depends upon the type of fuel burnt. Gaseous fuels require very less excess air. Liquid fuels require more excess air than for gaseous fuel and solids fuels require higher amounts of excess air than that required for liquid fuels. Gaseous fuels are burnt with 5 to 15% excess air, while liquid and solid fuels are burnt with 10 to 50% excess air.

4.5 Flue Gases

- Product gases which are produced by fuel burning are called flue gases.
- Flue gases contains CO_2, CO, H_2O, O_2, SO_2 and N_2.
- By Orsat analyzer we get molal analysis of flue gas.
- Orsat analyzer works on chemical absorption principle.
- A Fyrite apparatus is also used for determination of CO_2 and O_2 in dry flue gas manually.
- A Fyrite apparatus also works on chemical absorption principle.
- For oxygen measurement in flue gas on a continuous basis following methods are used :
    (i) Paramagnetic sensor
    (ii) Wet electrochemical cell
    (iii) Zirconium oxide ceramic cell
- The zirconium oxide ceramic cell is most preferred oxygen sensor for continuous monitoring of oxygen in hot dirty gases without considering sample conditions.
- The greater the water vapour present in the flue gas, higher is the dew point.
- Flue gas are the product gases which are produced by burning the fuel. Normally flue gases contains CO_2, CO, H_2O, O_2, SO_2, SO_3 and N_2. Concentration of SO_3 is very low in the flue gases.

Note :

1. All combustion reactions are exothermic.
2. Nitrogen reduces the flame temperature considerably and also accounts for high heat losses to stack.

Example 4.1   Crude oil is analysed to contain 87% carbon, 12.5% hydrogen and 0.5% sulphur (by weight). Calculate the net calorific value of crude oil at 298 K (25°C).
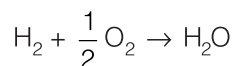
Data : Gross calorific value of crude oil at 298 K (25°C) is 45071 kJ/kg oil.

Latent heat of water vapour at 298 K (25°C) = 2442.5 kJ/kg.

Solution :

Basis : 1 kg of crude oil.

$$\text{Hydrogen burnt} = \text{Hydrogen in crude oil} = 0.125 \text{ kg}$$

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

$$1 \text{ kmol } H_2 \equiv 1 \text{ kmol } H_2O$$
$$2 \text{ kg of } H_2 \equiv 18 \text{ kg of } H_2O$$

$$\text{Water produced} = \frac{18}{2} \times 0.125 = 1.125 \text{ kg}$$

Latent heat of water vapour at 298 K (25°C)

$$= 1.125 \times \frac{2442.5}{1} = 2747.8 \text{ kJ}$$

$$\text{Net calorific value} = \text{Gross calorific value} - \text{Latent heat of water vapours}$$
$$= 45071 - 2747.8 = 42323.2 \text{ kJ/kg oil}$$

Method-II :
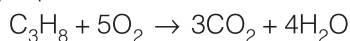$$\text{NCV} = \text{GCV} - \frac{\% \text{ hydrogen by wt.} \times 9 \times \lambda}{100}$$

$$= 45071 - \frac{12.5 \times 9 \times 2442.5}{100}$$

$$= 42323.2 \text{ kJ/kg of oil}$$

Example 4.2 The gross heating value (GHV) of gaseous propane at 298 K (25°C) is 2219.71 kJ/mol. Calculate its net heating value (NHV).

Solution :
Basis : 1 mol of gaseous propane.
$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$
$$1 \text{ mol } C_3H_8 \equiv 4 \text{ mole } H_2O$$
i.e., when 1 mol of C_3H_8 burnt, 4 moles of H_2O are produced.

$\therefore$
$$\text{Water produced} = 4 \times 18 = 72 \text{ g} = 72 \times 10^{-3} \text{ kg}$$
$$\text{NHV} = \text{Net heating value}$$
$$= \text{GHV} - \text{latent heat of water vapours}$$
$$= 2219.71 - 72 \times 10^{-3} \times 2442.5$$
$$= 2043.85 \text{ kJ/mol}$$

Example 4.3 Calculate the gross and net calorific values (i.e., GCV and NCV) of the natural gas at 298 K (25°C) having the following molar composition :

CH_4 : 89.4%, C_2H_6 : 5%, C_3H_8 : 1.9%, n-C_4H_{10} : 1%, CO_2 : 0.7% and N_2 : 2%
Data :

Component	GCV, kJ/mol	NCV, kJ/mol
CH_4	890.65	802.62
C_2H_6	1560.69	1428.64
C_3H_8	2219.17	2043.11
C_4H_{10}	2877.40	2657.32

Specific volume at 298 K (25°C) and 101.3 kPa = 24.465 m³/kmol.

Solution :
Basis : 1 mol of natural gas.
It contains 0.894 mol CH_4, 0.05 mol C_2H_6, 0.019 mol C_3H_8, 0.01 mol C_4H_{10}, 0.007 mol CO_2 and 0.02 mol N_2.
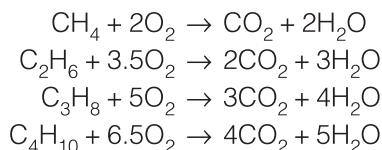In case of a gas mixture, the heating value (calorific value) of the gas mixture is sum of the heating values (calorific values) of the individual gases present in it.
$$\text{GCV} = 0.894 \times 890.65 + 0.05 \times 1560.69 + 0.019 \times 221904 + 0.01 \times 2877.40$$
$$= 945.21 \text{ KJ/mol natural gas}$$

$$NCV = 0.894 \times 802.62 + 0.05 \times 1428.64 + 0.019 \times 2043.11 + 0.01$$
$$= 854.37 \text{ KJ/mol natural gas}$$

Alternate calculation of NCV :

Combustion reactions are

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
$$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$$
$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$
$$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$$

$$\text{Total water formed} = \frac{2}{1} \times 0.894 + \frac{2}{1} \times 0.05 + \frac{4}{1} \times 0.019 + \frac{5}{1} \times 0.01$$
$$= 2.064 \text{ mol}$$

Weight of water produced $= 2.064 \times 18 = 37.152 \text{ g} = 37.152 \times 10^{-3} \text{ kg}$

Heat lost due to vaporisation of water

$$= 37.152 \times 10^{-3} \times \frac{2442.5}{1}$$
$$= 90.83 \text{ kJ/mol fuel}$$

$$\therefore \quad NCV = 945.21 - 90.83$$
$$= 854.38 \text{ kJ/mol natural gas}$$

M_{avg} = Average molecular weight of natural gas
$$= 0.894 \times 16 + 0.05 \times 30 + 0.019 \times 44 + 0.01 \times 58 + 0.007$$
$$\times 44 + 0.01 \times 28$$
$$= 18.088$$

$$GCV = \frac{945.21 \times 1000}{18.088} = 52256.2 \text{ kJ/kg}$$

$$NCV = \frac{854.37 \times 1000}{18.088} = 47234.1 \text{ kJ/kg}$$

Specific volume at 298 K (25°C) and 101.3 kPa = 24.465 m³/kmol

$$GCV = \frac{945.21 \times 1000}{24.465} = 38635.2 \text{ kJ/m}^3$$

$$NCV = \frac{854.37 \times 1000}{24.465} = 34922.13 \text{ kJ/m}^3$$

Example 4.4   The Orsat analysis of the flue gases from a boiler house chimney by volume is as given below : CO_2 : 11.4%, O_2 : 4.2% and N_2 : 84.4%.
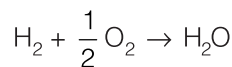
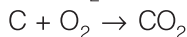Assuming that complete combustion takes place,

(i) calculate the % excess air

(ii) find the C : H ratio in the fuel

Solution :

Basis : 100 kmol of dry flue gas.

It contains 11.4 kmol CO_2, 4.2 kmol O_2 and 84.4 kmol N_2.

$$C + O_2 \rightarrow CO_2$$

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

$$O_2 \text{ accounted} = O_2 \text{ in } CO_2 + O_2 \text{ in flue gas as such}$$
$$= 11.4 + 4.2 = 15.6 \text{ kmol}$$
$$N_2 \text{ in the air} = N_2 \text{ in flue gas} = 84.4 \text{ kmol}$$

$$O_2 \text{ in supplied air} = \frac{21}{79} \times 84.4 = 22.435 \text{ kmol}$$

$$\text{Excess } O_2 = O_2 \text{ in flue gas} = 4.2 \text{ kmol}$$
$$O_2 \text{ unaccounted} = O_2 \text{ in air} - O_2 \text{ accounted}$$
$$= 22.435 - 15.6 = 6.835 \text{ kmol}$$

This O_2 must have been utilised for the burning of hydrogen of the fuel.

$$\text{Hydrogen burnt} = \frac{2}{1} \times 6.835 = 13.67 \text{ kmol}$$

$$\text{Theoretical } O_2 \text{ requirement} = 11.4 + 6.835 = 18.235 \text{ kmol}$$

$$\text{\% excess air = \% excess } O_2 = \left(\frac{22.435 - 18.235}{18.235} \right) \times 100 = 23.03$$

$$\text{Weight of carbon burnt} = 11.4 \times 12 = 136.8 \text{ kg}$$
$$\text{Weight of hydrogen burnt} = 13.67 \times 2 = 27.34 \text{ kg}$$

Carbon/hydrogen (w/w) ratio in the fuel

$$= \frac{136.8}{27.34} = 5.0$$

Example 4.5   The purge gas obtained from ammonia synthesis loop has the following molar composition : H_2 : 69%, N_2 : 23%, Ar : 2.7% and CH_4 : 5.3%

     It is burnt with 20% excess air. Calculate the theoretical air required and molar composition of the dry flue gas.

Solution :

Basis : 100 kmol of purge gas.

It contains 69 kmol H_2, 23 kmol N_2, 2.7 kmol Ar and 5.3 kmol CH_4.

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

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
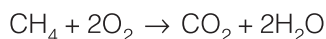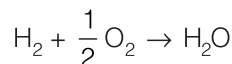
$$\text{Theoretical } O_2 \text{ required} = 0.5 \times 69 + 2 \times 5.3 = 45.1 \text{ kmol}$$

$$\text{Theoretical air required} = \frac{45.1}{0.21} = 214.8 \text{ kmol}$$

$$\text{Weight of theoretical air required} = 214.8 \times 29 = 6229.2 \text{ kg}$$

$$
\begin{aligned}
M_{avg} &= \text{average molecular weight of the purge gas} \\
&= 0.69 \times 2 + 0.23 \times 18 + 0.027 \times 40 + 0.053 \times 16 \\
&= 9.748
\end{aligned}
$$

$$\text{Weight of purge gas} = 100 \times 9.748 = 974.8 \text{ kg}$$

$$\text{Theoreitcal air required} = \frac{6229.2}{974.8} = 6.39 \text{ kg/kg purge gas}$$

$$O_2 \text{ in the air supplied} = 45.1 \times 1.20 = 54.12 \text{ kmol (20\% excess air)}$$

$$O_2 \text{ in the flue gas} = 54.12 - 45.1 = 9.02 \text{ kmol}$$

$$N_2 \text{ in the air supplied} = \frac{79}{21} \times 54.12 = 203.6 \text{ kmol}$$

$$N_2 \text{ in the flue gas} = 203.6 + 23 = 226.6 \text{ kmol}$$

$$CO_2 \text{ in the flue gas} = \frac{1}{1} \times 5.3 = 5.3 \text{ kmol}$$

$$Ar \text{ in the flue gas} = Ar \text{ in purge gas} = 2.7 \text{ kmol}$$

Flue gas composition (on dry basis) :

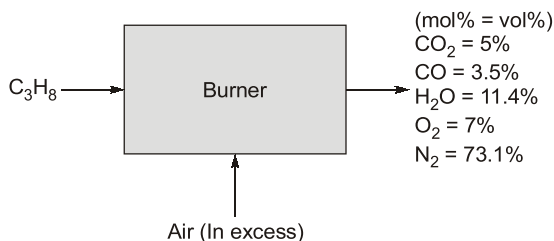| Component	Quantity, kmol	mole %
CO_2	5.3	2.18
Ar	2.7	1.11
O_2	9.02	3.70
N_2	226.6	93.01
Total	243.62	100.00

Example 4.6   Pure propane (C_3H_8) is burnt with an excess of air to give the following combustion product in volume percent:

$CO_2 = 5$, $CO = 3.5$, $H_2O = 11.4$, $O_2 = 7$, $N_2 = 73.1$

Calculate the percent excess air used.

Solution:

Basis: Product gases are 100 mol

Reaction:

(i) $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$

(ii) $C_3H_8 + \dfrac{7}{2}O_2 \rightarrow 3CO + 4H_2O$
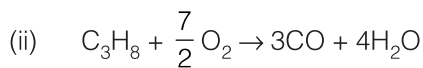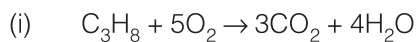
From stoichiometry or reaction (i), 3 mol of CO_2 is produced from 1 mol C_3H_8

From st. of rxn (ii) mol CO product 1 mol of C_3H_8

For 1 mol C_3H_8 complete combustion required = 5 mol O_2

In feed, $\quad\quad$ Total $C_3H_8 = \dfrac{5}{3} + \dfrac{3.5}{2} = 2.833$ mol

$\quad\quad$ Theoretical air required $= 2.833 \times \dfrac{5}{0.21} = 67.46$ mol

$\quad\quad$ Air actually used $= \dfrac{73.1}{0.79} = 92.53$ mol

Therefore, $\quad$ % excess air used $= \dfrac{92.53 - 67.46}{67.46} \times 100 = 37.2\%$

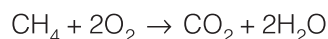**Example 4.7** $\quad$ Dry methane is burnt with dry air. Both are initially at 300 K. The theoretical flame temperature is 1570 K. If the complete combustion is assumed, how much excess air was used. Data: Mean molar specific heat value in J/mol K are:

CO_2 = 51.8 H_2O = 40.2, N_2= 32.2 and O_2 = 32.4

Standard heat of formation at 300 K = -8×10^5 J/mol of CH_4

Solution:
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
We know energy balance for adiabatic reaction:

Reactant heat + Heat released from reaction = Product heat

At 300 K $\Rightarrow$ Reactant heat = 0

Let 'a' be the moles of O_2 in the product gas

$\Rightarrow (1570 - 300)\left(51.8 + 2 \times 40.2 + a \times 32.4 + a \times \dfrac{79}{21} \times 32.2 + 32.2 \times 2 \times \dfrac{79}{21} \times 32.2\right) = 8 \times 10^5$

On Solving, $\quad\quad\quad\quad a = 1.664$ mol

$\quad\quad\quad\quad$ Excess $O_2 = 1.664$ mol

In the reaction O_2 used = 2 mol

$\quad\quad$ Now % excess air used $= \dfrac{1.669}{2} \times 100 = 83.2\%$

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Student's Assignments

Q.1 Calculate the net calorific value (NCV) at 298 K (25°C) at a sample of fuel oil having C/H ratio 9.33 (by weight) and containing sulphur to the extent of 1.3% by weight.
Data : The GCV of the fuel oil at 298 K (25°C) = 41785 kJ/kg
Latent heat of water vapour at 298 K (25°C) = 2442.5 kJ/kg

Q.2 A coal having 68.1% total carbon is burned to produce gases having the following composition by volume on the moisture free basis :
CO_2 : 12.4%, CO : 1.2%, O_2 : 5.4% & N_2 : 81%
Data :
1. Heating vlaue of coal = 28273.5 kJ/kg
2. Heat of combustion of CO = –283.18 kJ/mol
Calculate the standard heat of reaction in kJ/kg of coal burned.

Q.3 A furnace is fired with fuel oil. The Orsat analysis of the flue gases (by volume) is CO_2 : 10.6%, O_2 : 6% and N_2 : 83.4%. Calculate the percentage excess air and find the C : H ratio in the fuel oil. Assuming that the fuel does not contain nitrogen.

Q.4 One hundred mol per hour of butane (C_4H_{10}) and 5000 mol per hour of air are fed into a combustion reactor. Calculate the percent excess air.

Q.5 A fuel oil mixture containing 10% water rest hydrocarbon is burned with excess oxygen. The flue gas from combustion have following composition 9% CO_2, 2% CO, 5% O_2 and rest N_2 on dry basis (mole %).
(a) Calculate % excess air.
(b) Ratio of C to H on weight basis in hydrocarbon
(c) Amount of moisture present in flue gas per kg of oil burned.

Q.6 Dry methane is burned with dry air. Both are at 25°C initially. The flame temperature is 1300°C. If complete combustion is assumed how much excess air is being used? The reaction is
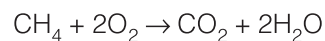
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
Standard heat of reaction = –8.028 × 10⁴ J/mol of CH_4 reacted. Mean molal specific heat of gases between 25°C and 1300°C are in J/(mol)(K). CO_2 = 51.88; H_2O = 40.45; O_2 = 34.01; N_2 = 32.21

Q.7 Bituminous coal with a calorific value of 20000 kJ/kg is used for generating steam in a boiler. How much coal has to be burnt to generate 1 MW of energy? Efficiency of combustion is 0.75. How much air is needed if 50% excess air is to be used? Assume that coal contains 67% carbon and 33% ash.

Q.8 A hydrocarbon is burnt with excess air. the Orsat analysis of the flue gas shows 10.81% CO_2, 3.78% O_2 and 85.41% N_2. Calculate the atomic ratio of C : H in the hydrocarbon and the % excess air.

Q.9 The Orsat analysis of a flue gas is :
CO_2 = 12.7%, O_2 = 7.1%, N_2 = 80.2%
Determine the percent excess air used in combustion. The nitrogen present in the flue gas is contributed by air only.

Q.10 An Orsat analysis of the combustion products of a hydrocarbon liquid fuel gave the following results : CO_2 = 10%, CO = 0.6%, O_2 = 5.7% and N_2 = 79% (by volume). The C/H ratio (by weight) of the liquid fuel is
(a) 1.06   (b) 3.18
(c) 6.36   (d) cannot determined

Q.11 Combustion requires
(a) a suppy of oxygen
(b) a combustible fuel
(c) a source of heat energy
(d) all of the above

Q.12 A fuel is a substance which
(a) burns on heating
(b) produces smoke
(c) burns to produce energy
(d) undergoes oxidation on heating

Q.13 Excess air is to be supplied for combustion to be complete due to
(a) its incomplete mixing
(b) obstruction of inert gas molecules
(c) chemical equilibrium
(d) undergoes oxidation on heating

Q.14 Which of the following is considered as combustion process?
(a) Oxidation of toluene to benzaldehyde
(b) Oxidation of hydrogen chloride to chlorine
(c) Oxidation of methane to carbon dioxide and water
(d) Oxidation of sulphur dioxide to sulphur trioxide

Q.15 Which of the following solids fuels has maximum gross calorific value?
(a) Coke   (b) Lignite
(c) Bagasse   (d) Rice husk

Q.16 Which of the following liquid fuels is not obtained from crude petroleum?
(a) Gasoline
(b) High speed diesel oil
(c) Aviation turbine fuel
(d) Biodiesel

■ ANSWERS

1. (39685.2)   2. (−64345.3)
3. (37.10, 5.71)   4. (61.6%)
5. (21%, 4.54, 1.558)   6. (96)   7. (0.7716)
8. (1/3, 19.97%)   9. (49.93)   10. (c)
11. (d)   12. (c)   13. (d)   14. (c)
15. (a)   16. (d)

■ Explanation

1.   (39685.2)
Basis : 1 kg of sample of fuel oil.
It contains 0.013 kg of sulphur and balance being C and H (as % S = 1.3)
Let x and y be kg of carbon and hydrogen in fuel oil.
Amount of C and H in fuel oil
$$= 1 - 0.013 = 0.987 \text{ kg}$$

$$x + y = 0.987$$
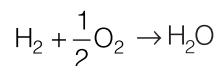and $$\frac{x}{y} = 9.33$$
(Given C/H ratio by weight = 9.33)
$$x = 9.33y$$
∴ $$9.33y + y = 0.987$$
$$10.33y = 0.987$$
∴ $$y = 0.09554 \text{ kg} \ \& \ x = 0.89146 \text{ kg}$$
Amount of hydrogen burnt = 0.09554 kg

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$
1 kmol H_2 ≡ 1 kmol H_2O
2 kg of H_2 ≡ 18 kg of H_2O

Water produced = $\dfrac{18}{2} \times 0.09554$ = 0.8597 kg

$$NCV = GCV - m\lambda$$
$$= 41785 - 0.8597 \times 2442.5$$
$$= 39685.2 \text{ kJ/kg fuel oil}$$

2.   (2.396)
Basis : 1 kmol of flue gas.
It contains 0.124 kmol CO_2, 0.012 kmol CO, 0.054 kmol O_2 and 0.81 kmol N_2.
C in CO_2 = 0.124 katom
C in CO = 0.012 katom
C in the coal = 0.124 + 0.012
$$= 0.136 \text{ katom}$$
$$= 0.136 \times 12 = 1.632 \text{ kg}$$
Coal contains 68.1% carbon. Therefore, based on 1.632 kg of C in the coal.

coal burned = $\dfrac{1.632}{0.681}$ = 2.396 kg

Heating value of 2.396 kmol coal
$$= 28273.5 \times 2.396 = 67743.3 \text{ kJ}$$
Heat of combustion of 0.012 kmol CO
$$= 0.012 \times (-283.18) \times 10^3 = -3398 \text{ kJ}$$
Standard heat of reaction
= (−heating value of coal) − heat of combustion of CO
$$= -67743.3 - (-3398)$$
$$= -64345.3 \text{ kJ/2.396 kg coal}$$

3.   (37.10, 5.71)
Basis : 100 kmol of flue gases.
It contains 10.6 kmol CO_2, 6 kmol O_2 and 83.4 kmol N_2.

O_2 accounted = O_2 in CO_2 + O_2 in flue gas
= $(1/1) \times 10.6 + 6 = 16.6$ kmol

Whatever N_2 is their in the flue gas that must come from the air supplied.

N_2 in the air supplied = N_2 in the flue gas
= 83.4 kmol

$\therefore$ O_2 in the air supplied

$$= \frac{21}{79} \times 83.4 = 22.17 \text{ kmol}$$

Matrial Balance of O_2 :

O_2 in the air supplied = O_2 accounted + O_2 unaccounted

O_2 unaccounted = O_2 in air supplied – O_2 accounted

O_2 unaccounted = $22.17 - 16.6 = 5.57$ kmol

This O_2 must have been utilised for the burning of hydrogen.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$
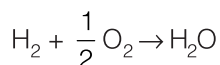
Hydrugen burnt = $\dfrac{1}{1/2} \times 5.57 = 11.14$ kmol

Theoretical O_2 requirement
= $10.6 + 5.57 = 16.17$ kmol

% excess air = % excess O_2

$$= \left(\frac{22.17 - 16.17}{16.17}\right) \times 100$$

$$= 37.10$$
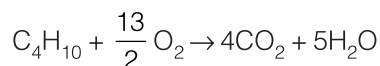
Weight of carbon burnt
= $10.6 \times 12 = 127.2$ kg

Weight of hydrogen burnt
= $11.14 \times 2 = 22.28$ kg

Carbon/hydrogen (w/w) ratio in the fuel oil
= $127.2/22.28 = 5.71$

4. **(a)**

First, calculate the theoretical air from the feed rate of fuel and stoichiometric equation for complete combustion of butane.

$$C_4H_{10} + \frac{13}{2}O_2 \rightarrow 4CO_2 + 5H_2O$$

$$(O_2)_{theoretical} = \frac{100 \text{ mol } C_4H_{10}}{h} \bigg| \frac{6.5 \text{ mol } O_2 \text{ required}}{\text{mol } C_4H_{10}}$$

$$= 650 \text{ mol } O_2/h$$

$$= (air)_{th} = \frac{650 \text{ mol } O_2}{h} \bigg| \frac{4.76 \text{ mol air}}{\text{mol } O_2}$$

$$= 3094 \text{ mol air/h}$$

Hence,

$$\% \text{ excess air} = \frac{(air)_{fed} - (air)_{th}}{(air)_{th}} \times 100\%$$

$$= \frac{5000 - 3094}{3094} \times 100\%$$

$$= 61.6\%$$

5. (21%, 4.54, 1.558)

Basis : 100 kmol of flue gas on dry basis.

(a) Amount of O_2 entered = $\dfrac{84}{0.79} \times 0.21$

$$= 22.33 \text{ kmol}$$

Excess of O_2 flue gas = 5 kmol

But if CO in the flue gas is converted to CO_2, then

Actual excess O_2 present in flue gas

$$= 5 - 2 \times \frac{1}{2} = 4 \text{ kmol}$$

$\therefore$ % excess $O_2 = \dfrac{4}{22.33 - 4} \times 100$

$$= \frac{4}{18.33} \times 100 = 21\%$$

(b) Net amount of C present in hydrocarbon.
(amount C in CO_2 + amount C in CO flue gas)
= $9 + 12 = 11$ kmol

Amount of combustible H_2 present in hydrocarbon can be calculated as

Net O_2 supplied
= [O_2 in CO_2 + O_2 in CO + O_2 consumed by hydrogen in hydrocarbon + unburned O_2] flue gas

$$22.33 = 9 + 2 \times \frac{1}{2} + x + 5$$

$\Rightarrow$ $x = 7.33$ kmol

$\therefore$ H_2 present in $H_2O = 2 \times 7.33 = 14.66$ kmol

Weight ratio of $\dfrac{C}{H} = \dfrac{11 \times 12}{14.66 \times 2} = \dfrac{132}{29.32}$

$$\frac{C}{H} = \frac{1}{0.22}$$

(c) Ratio of $\dfrac{C}{H} = \dfrac{1}{0.22}$