FUELS AND COMBUSTION

DR. ANUPAMA SAWANT

FUELS

Definition:

A combustible substance which when combusted completely produces large amount of heat energy which can be utilised economically for domestic as well as industrial purposes

During the process of combustion of a fuel, the elements carbon, hydrogen, etc combine with oxygen with simultaneous liberation of heat.

$$C + O_2 \longrightarrow CO_2 + \text{energy}$$

$$2H_2 + O_2 \longrightarrow 2H_2O + \text{energy}$$

FUELS

Classification:

- <u>On the basis of physical state -</u>

1. Solid fuels
2. Liquid fuels
3. Gaseous fuels

- <u>On the basis of source -</u>

1. Primary fuels – obtained from natural source
2. Secondary fuels – obtained from primary fuels

	SOLID	LIQUID	GASEOUS
PRIMARY	Wood, Coal	Petroleum (Crude oil)	Natural gas
SECONDARY	Charcoal, Metallurgical Coke	Petrol, Diesel, Kerosene	LPG, Water gas, Producer gas

Characteristics of a good fuel

- High Calorific Values
- Moderate Ignition Temperature
- Low Moisture Content
- Low Ash Content
- Moderate Velocity of Combustion
- Should not produce harmful products
- Low Cost
- Easy Storage & Transportation
- Easily Controllable

Calorific Value (C.V.)

Definition:

Calorific value is defined as the amount of heat energy generated when a unit quantity of fuel is completely oxidized (combusted).

Units of Calorific Value:

System	Solid/Liquid Fuels	Gaseous Fuels
CGS	Calories/gm	Calories/cm^3
MKS	k cal/kg	k cal/m^3
B.T.U	BTU/lb	BTU/ft^3

Higher and Lower Calorific Value

- **Higher Calorific Value or Gross Calorific Value (HCV or GCV)**

Higher Calorific value is defined as the total amount of heat energy generated when a unit quantity of fuel is completely oxidized (combusted) and products of combustion are allowed to cool to room temperature. (Latent heat of water vapour is taken into consideration)

- **Lower Calorific Value or Net Calorific Value (LCV or NCV)**

Lower Calorific value is defined as the total amount of heat energy generated when a unit quantity of fuel is completely oxidized (combusted) and products of combustion are allowed to escape to atmosphere. (Latent heat of water vapour is not taken into consideration)

- **LCV = HCV - Latent heat of condensation of water vapour produced**

Relation between HCV & LCV

Let the % of Hydrogen in fuel sample = H

Therefore amount of hydrogen in unit quantity of fuel

= H/100

Therefore amount of water vapour produced by unit quantity of fuel on complete combustion

= 9H/100 -------- ($H_2 + ½ O_2$ -----> H_2O)

Now, Latent heat of water Condensation = 587 kcal/kg

Therefore amount of heat energy liberated when water vapour from unit quantity of fuel is condensed

= 587 x 9H/100

$$\boxed{\text{LCV} = \text{HCV} - (587 \times 9H/100)}$$

Dulong's formula for calculation of HCV (kcal/kg)

$$HCV = 1/100\ [8080\ C + 34500\ (H - O/8) + 2240\ S]\ \text{kcal/kg}$$

where C, H, O, and S are the percentages of carbon, hydrogen, oxygen and sulphur in the fuel respectively.

- In this formula, oxygen is assumed to be present in combination with hydrogen as water

- LCV $= [\ HCV - 9H/100 \times 587]$ kcal/kg

  $= [\ HCV - 0.09\ H \times 587]$ kcal/kg

Numericals (Dulong's formula)

1. **Calculate the higher and lower calorific value of a coal which analyses: C = 74%, H = 6%, N = 1%, O = 9%, S = 0.8%, moisture = 2.2% and ash = 8%.**

Solution:

$$HCV = 1/100\ [8080\ C + 34500\ (H - O/8) + 2240\ S]\ kcal/kg$$

$$= 1/100\ [8080 \times 74 + 34500\ (6 - 9/8) + 2240 \times 0.8]\ kcal/kg$$

$$= 1/100\ [\ 597920 + 168187.5 + 1792\ ]\ kcal/kg$$

$$= 7678.995\ kcal/kg$$

$$LCV = HCV - (587 \times 9H/100)$$

$$= 7678.995 - 316.98$$

$$= 7362.015\ kcal/kg$$

Numericals (continued…)

2. A sample of coal has following analysis:

LCV = 8277.80 kcal/kg, C = 70 %, O = 8 %, N = 3%, S = 2% and Ash = 7 %. Calculate %H & HCV.

Solution:

HCV = 1/100 [8080 C + 34500 (H – O/8)+ 2240 S] kcal/kg ------- 1

HCV = LCV + (587 x 9H/100) ------- 2

Solving above equations simultaneously,

H = %

HCV = kcal/kg

FUELS & COMBUSTION -2

DR. ANUPAMA SAWANT

Proximate analysis of Coal

- Proximate analysis of coal gives good indication about heating and burning properties of coal.
- The test gives the composition of coal in respect of

1. moisture,
2. volatile matter,
3. Ash,
4. fixed carbon

- It is used to establish the rank of coals, to show the ratio of combustible to incombustible constituents, or to provide the basis for buying/selling, and otherwise evaluating coal for various purposes.

Important to know

- **What is MOISTURE ?**
- Moisture is the water that exists in the coal at the site, time, and under the conditions it is sampled.
- **What is VOLATILE MATTER ?**
- Volatile matter includes the components of coal, except for water, which are liberated at high temperature in the absence of oxygen. Volatile matter is a key health and safety concern as coals high in volatiles have an increased risk of spontaneous combustion.
- **What is ASH ?**
- The residue left after heating the coal sample.
- **What is FIXED CARBON ?**
- The solid combustible residue that remains after a coal has had the volatiles driven off.

Proximate Analysis (Procedure):

- Let the weight of coal sample taken = W g
- **Determination of Moisture Content**

A known sample of coal is heated in an electric hot oven at 105-110 C for one hour. After heating it is taken out from oven and cooled in a dessicator and weighed.

If the constant weight after heating = W1 g , Then General formula for determining the percentage of moisture content is ;

$$\% \text{ moisture} = (W - W1/W) \times 100$$

- Significance : Excess of moisture content is undesirable in coal, it reduces the calorific value of the coal.

- **Determination of Volatile Matter**

It is determined by heating a known weight of moisture free coal sample in a covered platinum crucible at 950 $\pm$ 20^0 C for 7 minutes. If the weight after heating is W2 g

$$\% \text{ volatile matter} = (W1 - W2)/ W \times 100$$

Significance : A high % of volatile matter reduces the calorific value of the coal such coal burns with low flame and high smoke.

Proximate analysis procedure contd…

- Determination of Ash

Ash content is determined by heating the residue left after the removal of volatile matter at 700 $\pm$ 20 ^{0}C for half an hour without covering.

If the constant weight obtained is W3 g

$$\% \text{ Ash} = W3/\ W \ \ X\ 100$$

- Significance : The high % of ash is undesirable as it reduces the calorific value of coal and rate of combustion also.

- Determination of Fixed carbon

Fixed carbon is the organic matter in the char, determined by the difference between 100 and the sum of the percentages of volatile matter, ash, and moisture.

$$\% \text{ Fixed Carbon} = 100 – [\% \text{ moisture} + \% \text{ Volatile matter} + \% \text{ Ash}]$$

- Significance : Higher the % of fixed carbon, Greater will be calorific value.

Numerical 1

2.5 g of coal sample was heated in oven at 110^0C for one hour. The weight obtained after heating was 2.41 g. The same sample was then analysed for volatile matter and weight obtained was 1.98 g. The sample was further heated to get the fixed weight of 0.246 g. calculate the results of proximate analysis.

Solution:

Weight of coal sample = W = 2.5 g

Weight of coal after heating at 110^0C = W1 = 2.41 g

% moisture = (W – W1/ W) X 100 = [(2.5 – 2.41)/ 2.5] X 100 = 3.6%

Weight of moisture free coal after heating for V.M. = W2 = 1.98 g

% volatile matter = (W1 – W2)/ W X 100 = [(2.41 – 1.98)/2.5] x 100 = 17.2 %

Weight of residue left after heating = W3 = 0.246 g

% Ash = W3/ W X 100 = (0.246/2.5) X 100 = 9.84 %

% Fixed Carbon = 100 – [% moisture + % Volatile matter + % Ash]

= 100 – (3.6 + 17.2 + 9.84)

= 69.36 %

Numerical 2

2.5 g of coal sample was heated in oven at 110^0C for one hour. The weight obtained after heating was 2.368 g. The same sample was then analysed for volatile matter and weight obtained was 1.75 g. The sample was further heated to get the fixed weight of 0.95 g. Calculate the results of proximate analysis

Solution:

Weight of coal sample = W = 2.5 g

Weight of coal after heating at 110^0C = W1 = 2.368 g

% moisture = (W – W1/W) X 100 = [(2.5 – 2.368)/ 2.5] X 100 = 5.28%

Weight of moisture free coal after heating for V.M. = W2 = 1.96 g

% volatile matter = (W1 – W2)/ W X 100 = [(2.368 – 1.75)/2.5] x 100 = 24.72 %

Weight of residue left after heating = W3 = 0.246 g

% Ash = W3/ W X 100 = (0.95/2.5) X 100 = 38 %

% Fixed Carbon = 100 – [% moisture + % Volatile matter + % Ash]

= 100 – (5.28 + 24.72 + 38)

= 32%

Ultimate Analysis of Coal

- **This method is to determine each element through chemical analysis and express it as a percentage of the total mass of the original coal or coke sample. Ultimate analysis tests produce more comprehensive results than the proximate analyses. Ultimate analysis determines the amount of**

1. **carbon,**
2. **hydrogen,**
3. **oxygen,**
4. **nitrogen, and**
5. **sulphur**

Determination of Carbon and Hydrogen

- A known amount of coal is taken in a combustion tube and is burnt in excess of pure oxygen. The carbon & Hydrogen in a coal sample are converted into Carbon dioxide and Water respectively.
- The product of combustion CO2 and H2O are produced in KOH & CaCl2 tubes of known weights respectively.
- <u>Combustion of Carbon:</u>

$$C + O_2 \rightarrow CO_2$$

12 32 44

Therefore

% of Carbon = 12/44 (Increase in wt. of KOH tube) / (wt. of coal sample) x 100

- <u>Combustion of Hydrogen:</u>

$$H_2 + 1/2\ O_2 \longrightarrow H_2O$$

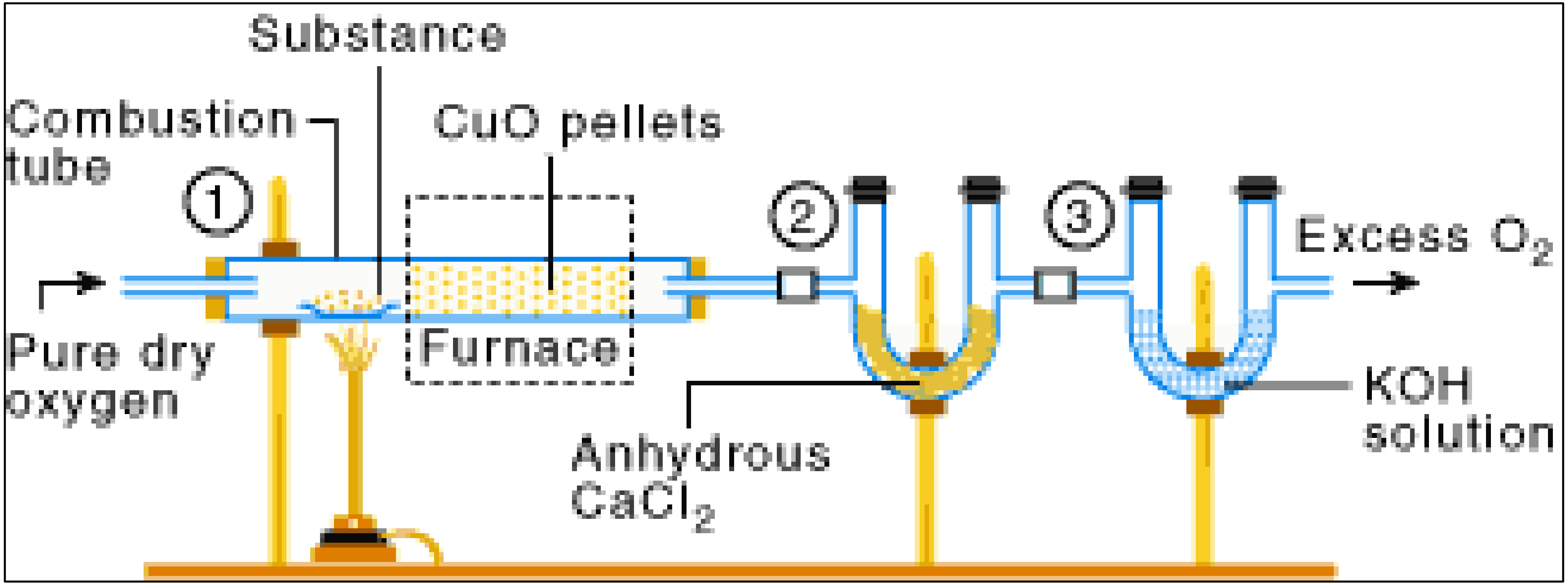
2 16 18

Therefore

% of Hydrogen = 2/18 (Increase in wt. of CaCl2 tube) / (wt. of coal sample) x 100

- <u>Significance</u> : High % of Carbon and Hydrogen increases the calorific value of the coal.

Determination of carbon and hydrogen



Numerical 1

1.5 g of coal was taken for C & H determination. The increase in the weight of CaCl2 tube and Potash bulb was 1.25g and 4.88g respectively. Calculate % C & %H.

Solution:

Weight of coal sample = 1.5 g

Increase in the weight of CaCl2 tube = 1.25g

Increase in the weight of Potash bulb = 4.88g

% of Carbon = 12/44 (Increase in wt. of KOH tube) / (wt. of coal sample) x 100

= 12/44 (4.88/1.5) X 100

= 88.72 %

% of Hydrogen = 2/18 (Increase in wt. of CaCl2 tube) / (wt. of coal sample) x 100

= 2/18 (1.25/1.5) X 100

= 9.25

Numerical 2

An organic compound contains 69% carbon and 4.8% hydrogen, the remainder being oxygen. Calculate the masses of carbon dioxide and water produced when 0.20 g of this compound is subjected to complete combustion.

Step I. Calculation of mass of CO_2 produced

Mass of compound = 0.20 g

Percentage of carbon = 69%

$$\text{Percentage of carbon} = \frac{12}{44} \times \frac{\text{Mass of carbon dioxide formed}}{\text{Mass of compound}} \times 100$$

$$69 = \frac{12}{44} \times \frac{\text{Mass of carbon dioxide formed}}{(0.20\text{ g})} \times 100$$

$$\therefore \text{ Mass of } CO_2 \text{ formed} = \frac{69 \times 44 \times (0.20\text{ g})}{12 \times 100} = \mathbf{0.506\text{ g}}$$

Step II. Calculation of mass of H_2O produced

Mass of compound = 0.20 g

Percentage of hydrogen = 4.8%

$$\text{Percentage of hydrogen} = \frac{2}{18} \times \frac{\text{Mass of water formed}}{\text{Mass of compound}} \times 100$$

$$4.8 = \frac{2}{18} \times \frac{\text{Mass of water formed}}{(0.20\text{ g})} \times 100$$

$$\therefore \text{ Mass of } H_2O \text{ formed} = \frac{4.8 \times 18 \times (0.20\text{ g})}{2 \times 100} = \mathbf{0.0864\text{ g}}$$

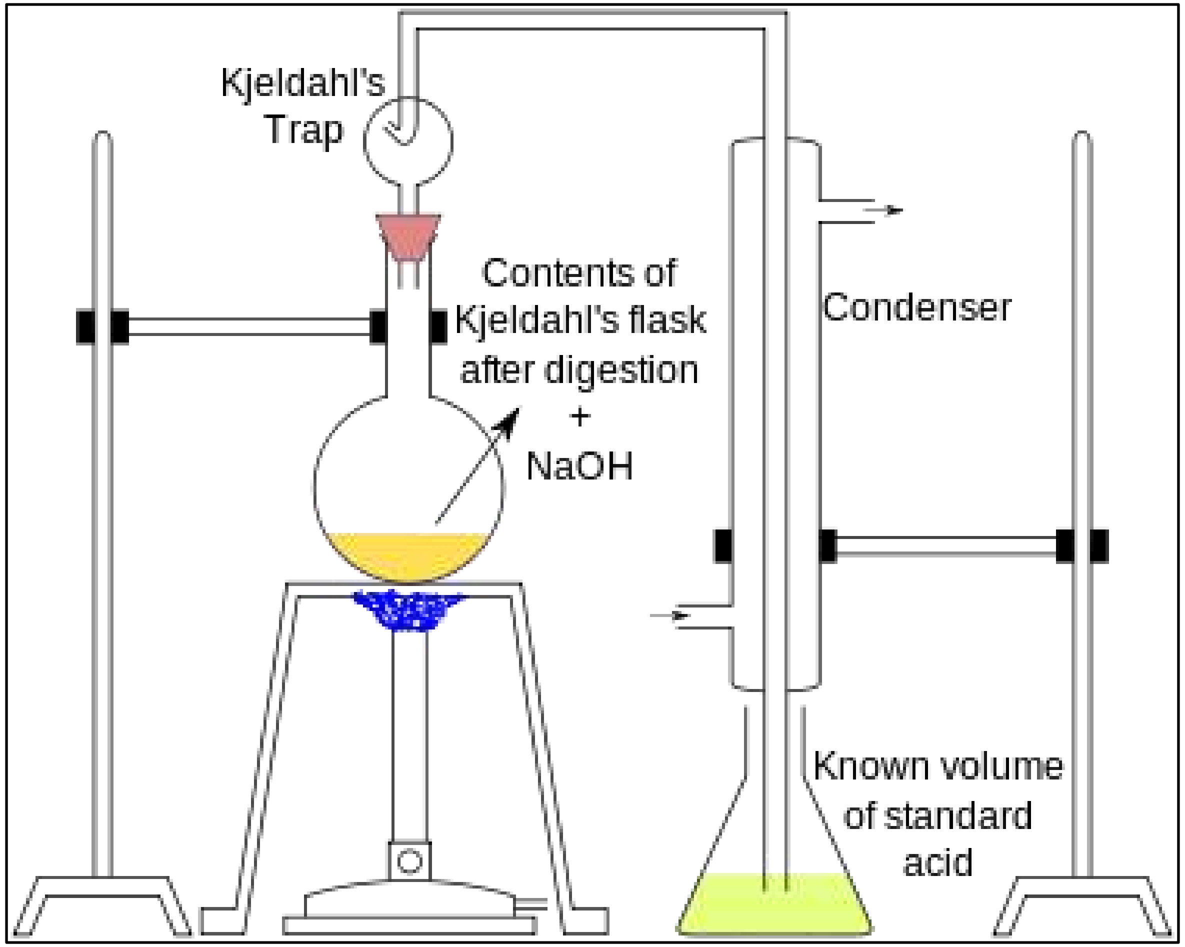
Determination of nitrogen by Kjeldahl's method

- Nitrogen present in coal sample can be estimated by Kjeldahl's method.
- 1 g of Coal sample is heated with conc. H_2SO_4 & K_2SO_4 (as a catalyst) in a long necked flask, called Kjeldahl's flask.
- Nitrogen is converted into ammonium sulphate. The ammonium sulphate is heated with excess of NaOH & liberate ammonia. The liberated ammonia is absorbed in standard solution of H_2SO_4.
- The unused acid is determined by back titration with standard NaOH. From the volume of acid used by ammonia liberated, the % of N can be calculated

% Nitrogen = {(Vol. of acid used) x normality x 1.4} / (wt. of coal sample)

- Significance : Nitrogen is an inert and Non- combustible material. It has no calorific value so it is undesirable.

Determination of nitrogen by Kjeldahl's method



Calculation of % N

$N \xrightarrow{H_2SO_4} (NH_4)_2SO_4 \xrightarrow{NaOH} NH_3$ gas ---> absorbed in H_2SO_4 ----> $(NH_4)_2SO_4$---> titrated against standard NaOH

Coal

1000ml 1N NaOH = 1000 ml 1N H_2SO_4 =1000ml 1N NH_3 = 17 g NH_3 = 14 g N

Let

Volume of x N NaOH required for Blank titration (H_2SO_4 taken) = V1 ml

Volume of x N NaOH required for Back titration (H_2SO_4 unused) = V2 ml

Therefore,

Volume of NaOH corresponding to H_2SO_4 used = (V1 – V2) ml

1000ml 1N NaOH = 14 g N

(V1 – V2) ml x N NaOH $= \dfrac{14 \times (V1 - V2) \times x}{1000}$ g N -------(This is the Nitrogen present in W g of coal)

Therefore, $\% N = \dfrac{14 \times (V1 - V2) \times x}{1000 \times W} \times 100$

% Nitrogen = [1.4 x (Vol. of acid used) x normality] / (wt. of coal sample)

Numerical 1

1 g coal sample was used for determination of nitrogen. The liberated ammonia was absorbed in 50 ml of H_2SO_4. The excess acid required 42 ml of 0.1 N NaOH for neutralisation while for blank titration 50 ml of same NaOH was required. Calculate % N.

Solution:

Volume of 0.1 N NaOH required for Blank titration (H_2SO_4 taken) = 50 ml

Volume of 0.1 N NaOH required for Back titration (H_2SO_4 unused) = 42 ml

Therefore,

Volume of NaOH corresponding to H_2SO_4 used by NH_3 = (50 – 42) ml

% Nitrogen = [1.4 x (Vol. of acid used by NH_3) x normality] / (wt. of coal sample)

= 1.4 X (50 – 42) X 0.1 / 1

= 1.12 %

Determination of Sulphur

- A known amount of coal sample is burnt completely in bomb calorimeter in presence of oxygen where sulphur converts into sulphates.
- The % of Sulphur is determined by the washings of bomb calorimeter. The washings are treated with Barium Chloride solution which makes Barium Sulphate precipitate.

$$BaCl_2 + H_2SO_4 \text{ -----> } BaSO_4 + 2HCl$$

$$1\ BaSO_4 = 1\ S$$

$$233 \qquad 32$$

Therefore,

% Sulphur = 32/233 x (wt. of precipitate) / (wt. of coal sample) x 100

- **Significance** : Sulphur has its calorific value and hence it contributes to the calorific value of fuel. However, the combustion product of Sulphur i.e SO2, SO3 cause air pollution and corrosion of equipment.

Numerical

2.5 g of coal sample in quantitative analysis gave 0.42 g $BaSO_4$. Calculate % sulphur.

Solution:

Weight of coal sample = 2.5 g

Weight of $BaSO_4$ formed = 0.42 g

% Sulphur = 32/233 x (wt. of $BaSO_4$ precipitate) / (wt. of coal sample) x 100

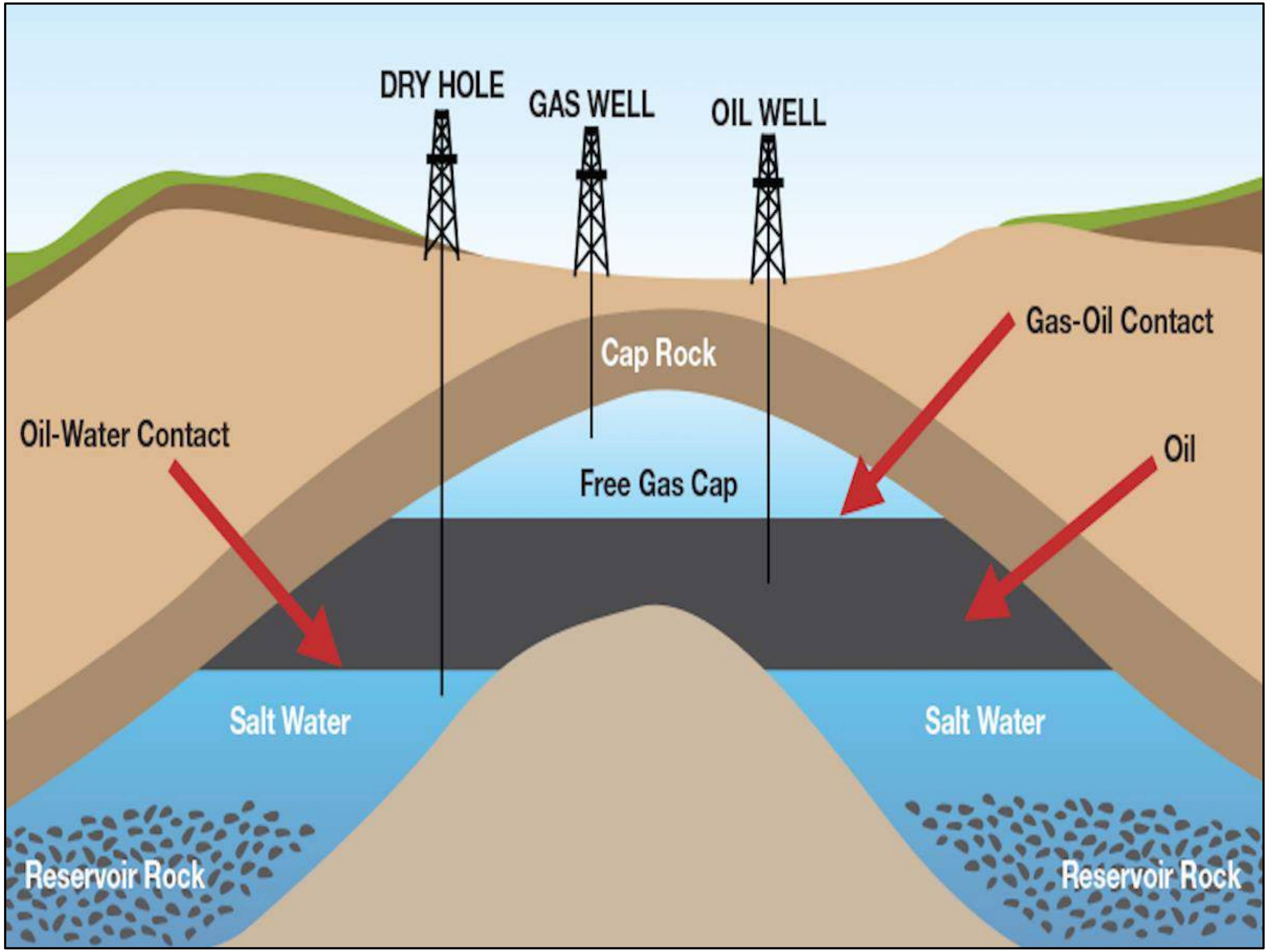
= 32/233 X (0.42/ 2.5) X 100

= 2.30 g

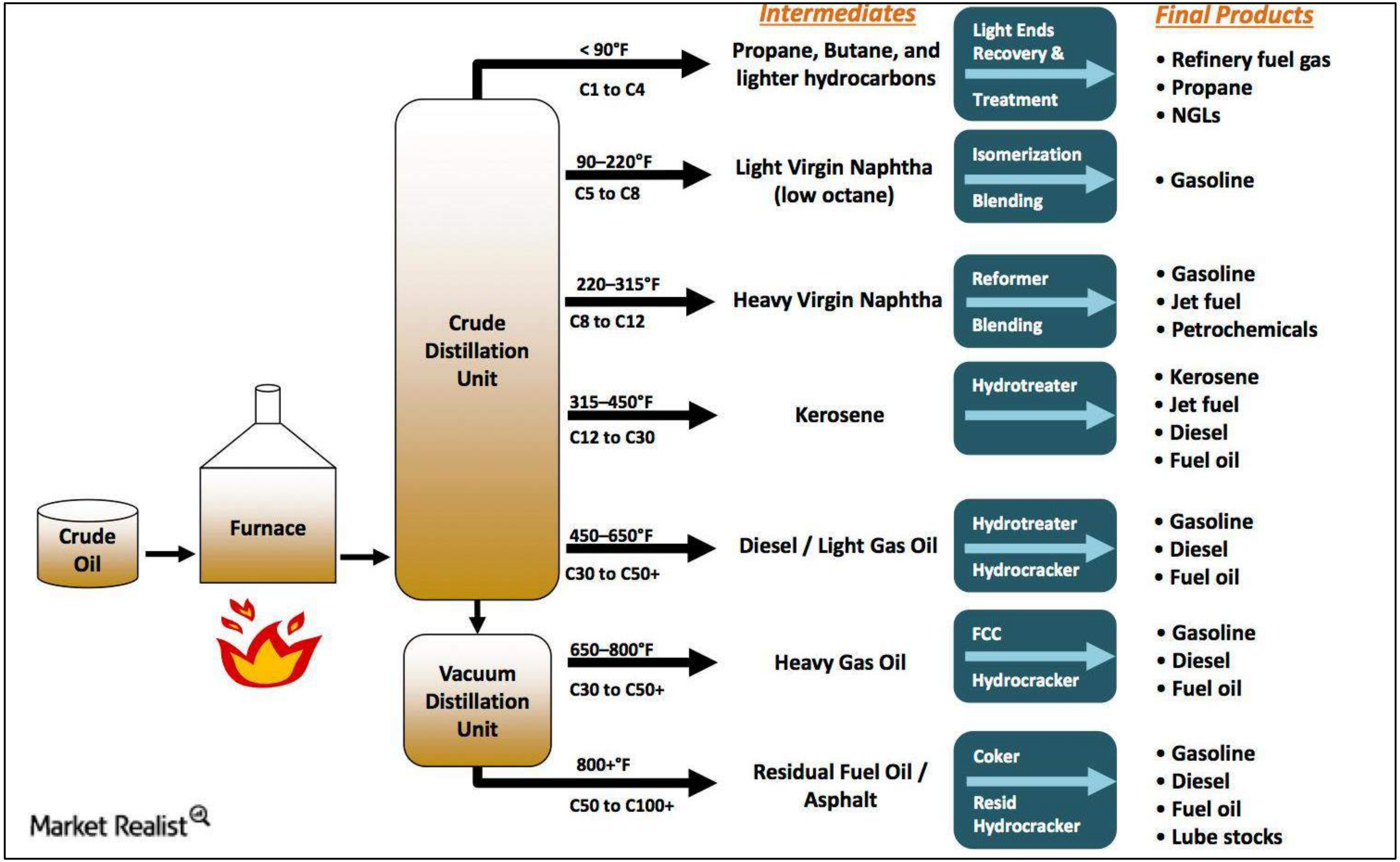
FUELS AND COMBUSTION - 3

DR. ANUPAMA SAWANT

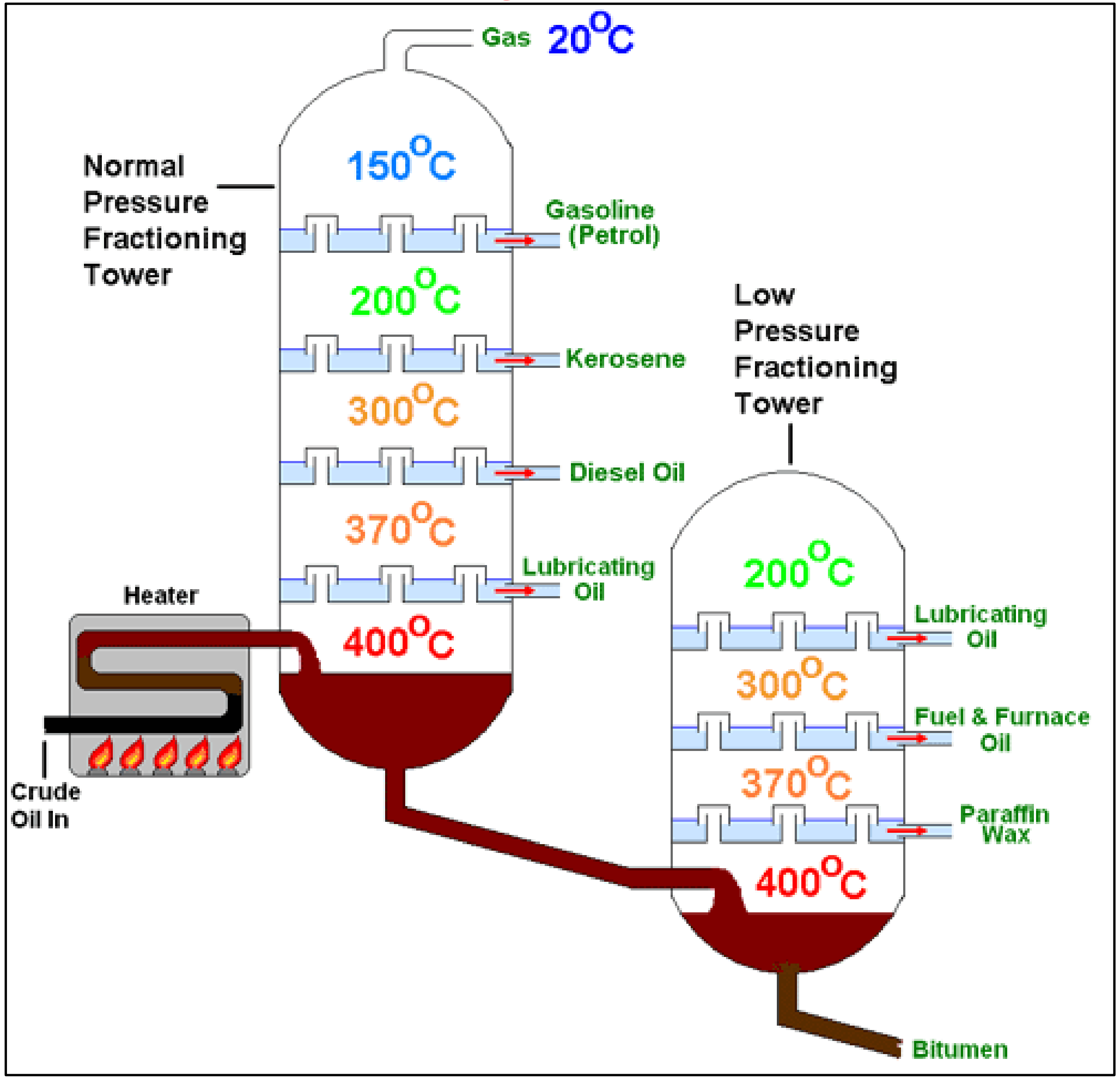
Mining of petroleum (Crude Oil)



Fractional Distillation of Petroleum (Crude Oil)



Vacuum Distillation of Heavy oil

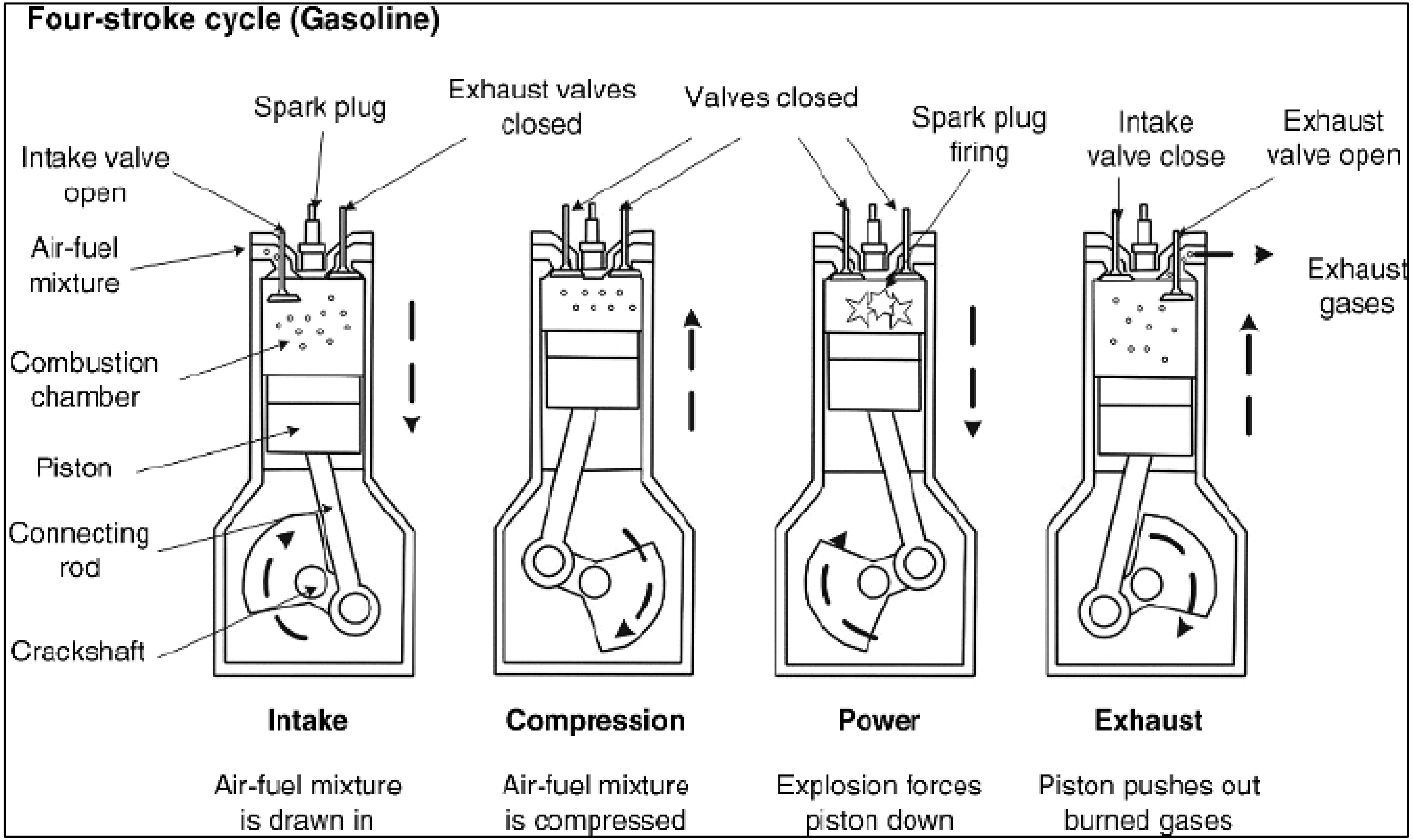


Refineries

Petrol (Gasoline) - Knocking

- **Knocking, in an Internal Combustion Engine, is sharp metallic sounds caused by premature combustion of part of the compressed air-fuel mixture in the cylinder.**
- **In a properly functioning engine, the charge burns with the flame front progressing smoothly from the point of ignition across the combustion chamber. However, at high compression ratio, depending on the composition of the fuel, some of the charge may spontaneously ignite ahead of the flame front and burn in an uncontrolled manner, producing intense high-frequency pressure waves. These pressure waves force parts of the engine to vibrate, which produces an audible knock.**
- **Knocking can cause overheating of the spark-plug points, erosion of the combustion chamber surface, and rough, inefficient operation.**

Working of Internal Combustion Engine



Octane Number

- Octane number of a fuel defines percentage of Iso-octane present in the mixture of Iso-octane and n-heptane under standard operating conditions.
- Octane rating signifies the ability to resist auto ignition when used in the gasoline engine.
- Due to compression of air and fuel together, gasoline tends to ignite at the end of compression by spark created by spark plug.
- The fuel having high octane number takes more time to burn but provides maximum efficiency to the gasoline engine
- Opposite to it fuel having low octane number tends to adopt auto combustion easily due to the effect of excess heat and pressure.

Octane Number

- The octane number of a fuel is measured in a test engine, and is defined as the percentage, by volume, of iso-octane (2,2,4-trimethylpentane, an isomer of octane) in the mixture of iso-octane and n-heptane which would have the same anti-knocking capacity as the fuel under test.
- By definition, iso-octane is assigned an octane number 100 and heptane is assigned an octane number zero.

e.g. gasoline with the same knocking characteristics as a mixture of 90% iso-octane and 10% heptane would have an octane number 90.

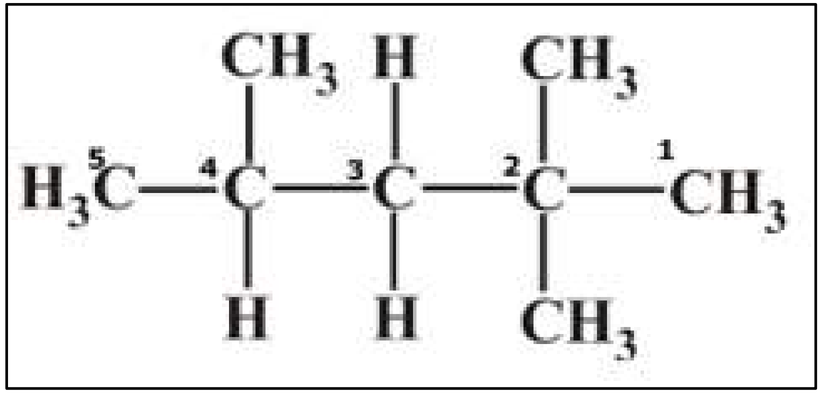
Note:

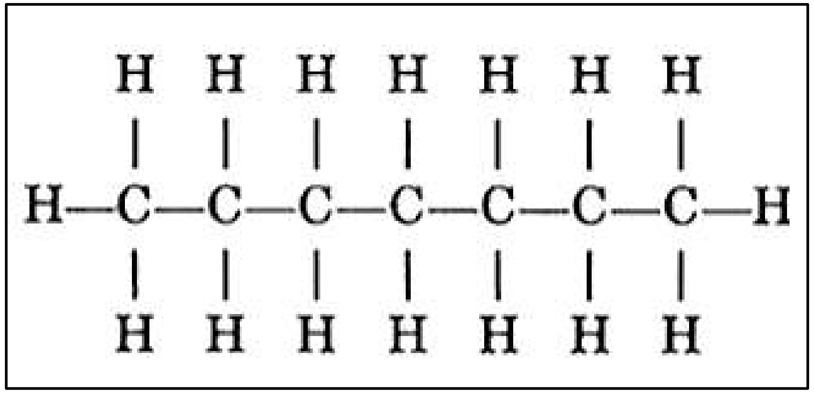
1. This does not mean, however, that the gasoline actually contains these hydrocarbons in these proportions. It simply means that it has the same detonation resistance as the described mixture.
2. Because some fuels are more knock-resistant than iso-octane, the definition has been extended to allow for octane numbers higher than 100.

e.g. Racing fuels, LPG, and alcohol fuels such as methanol or ethanol can have octane number of 110 or significantly higher - ethanol's Octane Number is 129

3. Octane rating does not relate to the energy content of the fuel. It is only a measure of the fuel's tendency to burn rather than explode.

Structures





Iso-octane (2,2,4-trimethylpentane)

n-heptane

Factors affecting Octane Number

Factors affecting Octane Number

1. The shorter the chain the higher the octane number

Heptane C_7H_{16} = 0

Hexane C_6H_{14} = 25

Pentane C_5H_{12} = 62

Butane C_4H_{10} = 94

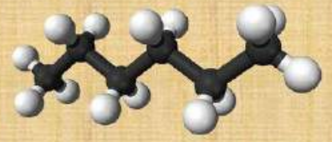
Factors affecting Octane Number

2. The more branched the chain the higher the octane number

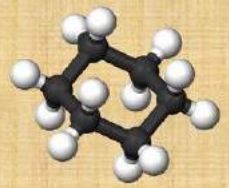
- E.g. C_7H_{16}
  - Heptane = 0
  - 2-methylhexane = 65
  - 2,3 dimethylpentane = 91

Factors affecting Octane Number

3. Cyclic compounds have a higher octane number than straight chain compounds



Hexane = 25

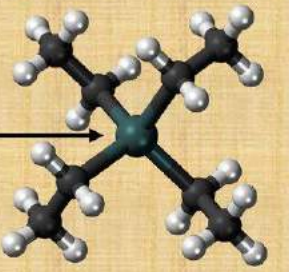


Cyclohexane = 83

Factors affecting Octane Number

4. Adding compounds such as tetraethyl lead or MTBE (methyl tertiary butyl ether)

Lead



MTBE Octane Number = 118

Antiknocking agents

- **Definition:**

Anti Knocking agents are the additives added in small quantities in petrol engine to reduce the knocking tendency.

- Typical "octane booster" gasoline additives include tetra-ethyl lead, MTBE and toluene.
- Tetra-ethyl lead (the additive used in leaded gasoline) is easily decomposed to its component radicals, which react with the radicals from the fuel and oxygen that start the combustion, thereby delaying ignition and leading to an increased octane number.
- However, tetra-ethyl lead and its byproducts are poisonous and tetra-ethyl lead's use creates an environmental hazards. In order to help the simultaneous elimination of Pb formed, a small amount of ethylene dibromide (Scavenger) is also added to petrol.

$$Pb + BrCH_2\text{-}CH_2Br \text{ ----> } PbBr_2 + CH_2 = CH_2$$

Eventually this Lead bromide is equally harmful to the environment.

Unleaded Petrol

- Beginning in the 1970s, use of TEL in the United States and most of the industrialized world has been restricted. Its use is currently limited to being an additive to aviation gasoline.
- Now a days most of countries are phasing out leaded fuel and focusing on various anti knock additives. There are three major group of anti knock agents.

➢ **Aromatics:**

Toluene and xylene are the main aromatic organic solvents usually found in anti knock additives. Toluene is a clear, water insoluble liquid. The properties of toluene and xylene are nearly identical. They are both octane boosters. They are also not bad for human health because of carcinogenic nature like benzene.

➢ **Oxygenates:**

Ethanol is most widely blended with gasoline. Similar type of octane enhancement can be obtained by methanol, isopropyl alcohol and tertiary butyl alcohol. The either is most widely used as a gasoline additive by refiners is MTBE (methyl tertiary butyl ether).MTBE is soluble with water therefore its use as an anti knock agent is controversial. ETBE (ethyl tertiary butyl ether) are good octane enhancing ether additives.

➢ **Organo-metallic compounds:**

Organometallic compounds have environmental and health issues of human.

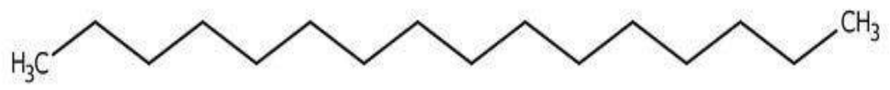
Cetane Number

- The cetane number of a fuel is defined as the volume percent of n-hexadecane (Cetane) in a blend of cetane and 1-methyl naphthalene (α – methyl naphthalene) that gives the same ignition delay period as the test sample.

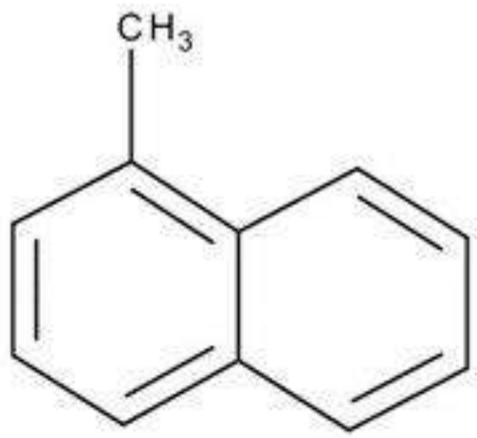
e.g. A fuel with a cetane number of 50 will have the same performance in the engine as a blend of 50% cetane and 50% 1-methylnaphthalene.

- The Cetane Number is a measure of a fuel's ignition delay, the time period between the start of injection and the first identifiable pressure increase during combustion of the fuel. In a particular diesel engine, higher cetane fuels will have shorter ignition delay periods than lower cetane fuels.
- Cetane number of a diesel engine fuel is indicative of its ignition characteristics. Higher the cetane number better it is in its ignition properties.
- Cetane number affects a number of engine performance parameters like combustion, stability, drivability, white smoke, noise and emissions of CO and HC.

Structures



Cetane (n- hexadecane)



1- methyl naphthalene

Comparison between Octane Number and Cetane Number

Octane Number	Cetane Number
• Octane number measures the performance of <u>gasoline</u>. • Octane Number measures the <u>ability of a fuel to resist pre-ignition</u> of the gasoline. • <u>Higher</u> Octane number gives <u>better quality</u> petrol • Fuel having <u>higher octane number</u> tends to ignite rapidly gives <u>fewer tendencies to knock</u> in Gasoline engine. • Octane number is decided according to the ignition of <u>Iso-octane</u> which is 100 and zero for <u>n-heptane</u>	• Cetane number measure the performance of the <u>diesel</u>. • Cetane Number measures the <u>ignition delay</u> of the diesel • <u>Higher</u> Cetane number defines <u>better quality</u> diesel. • Fuel having <u>higher cetane value</u> shows readily ignition and gives <u>fewer tendencies to knock</u> in the diesel engine • Cetane rating is measured according to the ignition of the <u>cetane</u> which is 100 and <u>1-methylnaphthalene</u> which is zero

Catalytic Convertor

- A catalytic converter is a large metal box, bolted to the underside of your car, that has two pipes coming out of it. One of them (the converter's "input") is connected to the engine and brings in hot, polluted fumes from the engine's cylinders (where the fuel burns and produces power). The second pipe (the converter's "output") is connected to the tailpipe (exhaust). As the gases from the engine fumes blow over the catalyst, chemical reactions take place on its surface, breaking apart the pollutant gases and converting them into other gases that are safe enough to blow harmlessly out into the air.
- One very important thing to note about catalytic converters is that they require you to use unleaded fuel, because the lead in conventional fuel "poisons" the catalyst and prevents it from taking up the pollutants in exhaust gases.

Catalytic converters (contd…)

Working

- Inside the converter, the gases flow through a dense honeycomb structure made from a ceramic and coated with the catalysts (Rhodium). The honeycomb structure means the gases touch a bigger area of catalyst at once, so they are converted more quickly and efficiently.
- Typically, there are two different catalysts in a catalytic converter:
- One of them tackles nitrogen oxide pollution using a chemical process called reduction (removing oxygen). This breaks up nitrogen oxides into nitrogen and oxygen gases (which are harmless, because they already exist in the air around us)

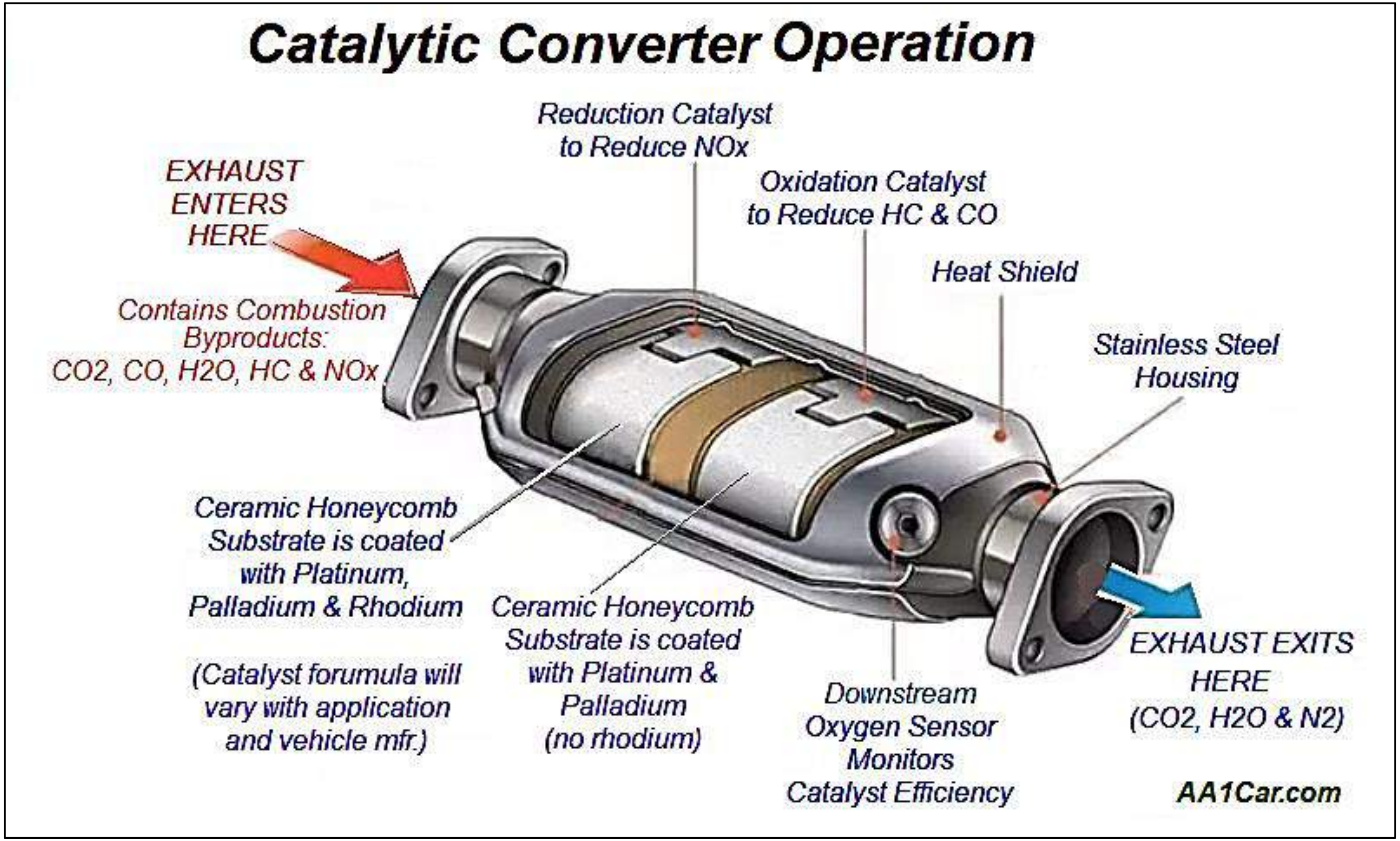
$$2\,NO_x \;\text{----->}\; N_2 + x\,O_2$$

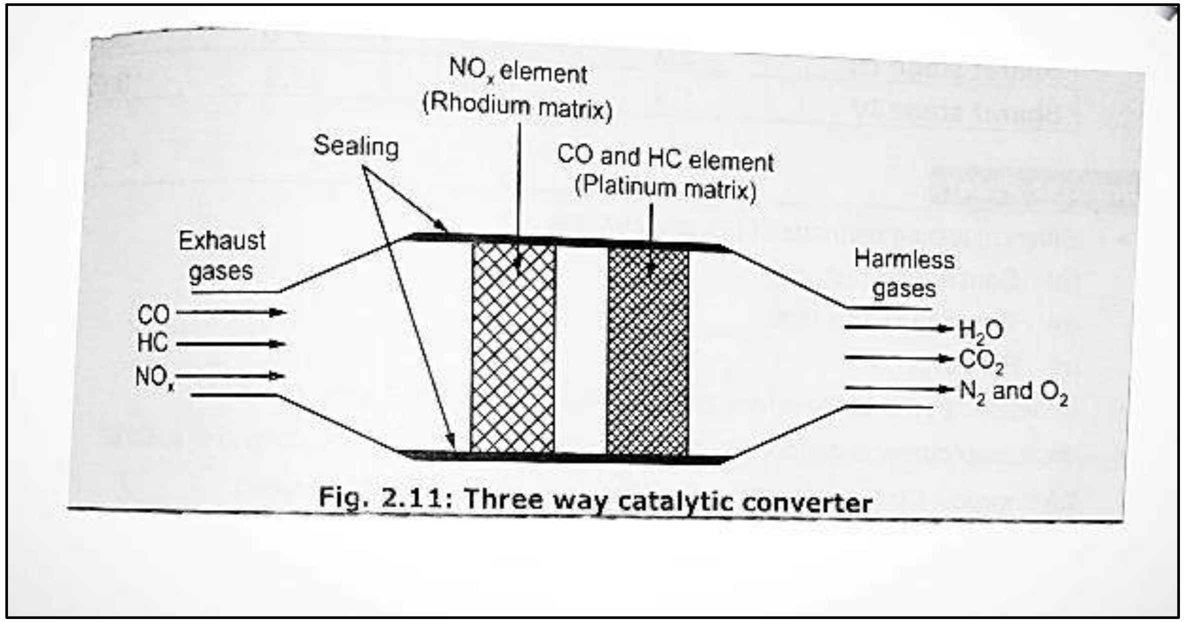
- The other catalyst works by an opposite chemical process called oxidation (adding oxygen) and turns carbon monoxide into carbon dioxide. Another oxidation reaction turns unburned hydrocarbons in the exhaust into carbon dioxide and water.

$$2CO + O_2 \;\text{----->}\; 2CO_2$$

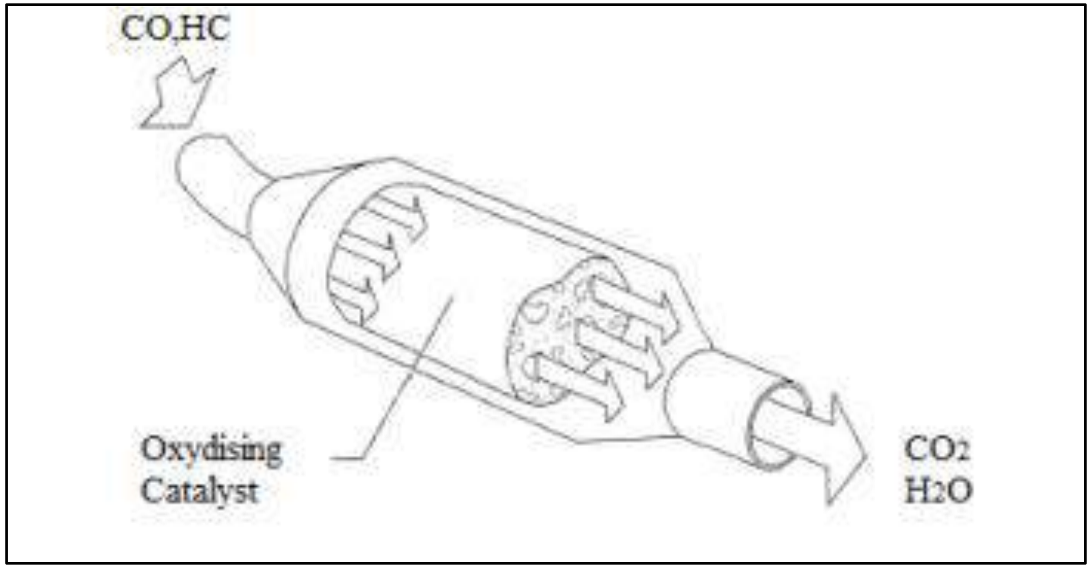
$$HC + O_2 \;\text{----->}\; CO_2 + H_2O$$

- In effect, three different chemical reactions are going on at the same time. That's why we talk about three-way catalytic converters. (Some, less-effective converters carry out only the second two (oxidation) reactions, so they're called two-way catalytic converters.) After the catalyst has done its job, what emerges from the exhaust is mostly nitrogen, oxygen, carbon dioxide, and water (in the form of steam)


Catalytic Converter Operation
Reduction Catalyst to Reduce NOx
EXHAUST ENTERS HERE
Oxidation Catalyst to Reduce HC & CO
Heat Shield
Contains Combustion Byproducts: CO2, CO, H2O, HC & NOx
Stainless Steel Housing
Ceramic Honeycomb Substrate is coated with Platinum, Palladium & Rhodium
Ceramic Honeycomb Substrate is coated with Platinum & Palladium (no rhodium)
EXHAUST EXITS HERE (CO2, H2O & N2)
(Catalyst forumula will vary with application and vehicle mfr.)
Downstream Oxygen Sensor Monitors Catalyst Efficiency
AA1Car.com



Three way catalytic converter



Two way catalytic converter

COMBUSTION OF FUEL (NUMERICALS)

1. A solid fuel has C= 80%, H = 12%, O = 8%. Calculate the minimum quantity of air required for complete combustion of 1 kg of fuel

Solution:

Constituent	% by weight	Weight per kg
C	80	0.80
H	12	0.12
O	8	0.08

$C + O_2 \dashrightarrow CO_2$ $H_2 + 1/2\ O_2 \dashrightarrow H_2O$

12   32   2   16

0.8 ---- 2.13 kg   0.12 ---- 0.96kg

Total amount of oxygen required = 2.13 + 0.96 = 3.09 kg

Net amount of oxygen required = 3.09 – 0.08 = 3.01 kg

Air contains 23% oxygen by weight,

Amount of air required = (3.01) X 100/23

= 13.09 kg

FUELS AND COMBUSTION – 4
(COMBUSTION NUMERICALS)

DR. ANUPAMA SAWANT

Numerical 1

A solid fuel has C= 80%, H = 12%, S = 1%, N = 1%, Moisture = 1%, O = 5%. Calculate the minimum quantity of air required for complete combustion of 1 kg of fuel

Solution:

Constituent	% by weight	Weight per kg
C	80	0.80
H	12	0.12
S	1	0.01
O	5	0.05

$C + O_2 \longrightarrow CO_2$

12 32

0.8 ---- 2.13 kg

$H_2 + 1/2\ O_2 \longrightarrow H_2O$

2 16

0.12 ---- 0.96 kg

$S + O_2 \longrightarrow SO_2$

32 32

0.01 ----- 0.01 kg

Total amount of oxygen required = 2.13 + 0.96 + 0.01 = 3.10 kg

Net amount of oxygen required = 3.10 – 0.05 = 3.05 kg

Air contains 23% oxygen by weight,

Amount of air required = (3.05) X 100/23

= 13.26 kg

Numerical 2

A solid fuel has C= 80%, H = 12%, S = 1%, N = 1%, Moisture = 1%, O = 5%. Calculate the minimum quantity of air required for complete combustion of 1 kg of fuel if 30% excess air is supplied.

Solution:

Constituent	% by weight	Weight per kg
C	80	0.80
H	12	0.12
S	1	0.01
O	5	0.05

$C + O_2 \longrightarrow CO_2$

12 32

0.8 ---- 2.13 kg

$H_2 + 1/2\ O_2 \longrightarrow H_2O$

2 16

0.12 ---- 0.96 kg

$S + O_2 \longrightarrow SO_2$

32 32

0.01 ----- 0.01 kg

Total amount of oxygen required = 2.13 + 0.96 + 0.01 = 3.10 kg

Net amount of oxygen required = 3.10 – 0.05 = 3.05 kg

Air contains 23% oxygen by weight,

Amount of air required = (3.05) X 100/23 = 13.26 kg

If 30% excess air is supplied the amount of air required = 13.26 X 130/100

= 17.37 kg

Numerical 3

A solid fuel has C= 80%, H = 12%, S = 1%, N = 1%, Moisture = 1%, O = 5%. Calculate the weight and volume of air required for complete combustion of 1 kg of fuel. (Molecular weight of air = 28.94)

Solution:

Constituent	% by weight	Weight per kg
C	80	0.80
H	12	0.12
S	1	0.01
O	5	0.05

C + O2 ----> CO2
12 32
0.8 ---- 2.13 kg

H2 + 1/2 O2 ----> H2O
2 16
0.12 ---- 0.96 kg

S + O2 ----> SO2
32 32
0.01 ----- 0.01 kg

Total amount of oxygen required = 2.13 + 0.96 + 0.01 = 3.10 kg

Net amount of oxygen required = 3.10 – 0.05 = 3.05 kg

Air contains 23% oxygen by weight,

Amount of air required = (3.05) X 100/23 = 13.26 kg

For air, 28.94 = 22.4 m^3

Therefore, 13.26 kg = 13.26 X (22.4/28.94) m^3

= 10.26 m^3

Points to remember (For numericals on combustion of fuel)

1. When oxygen and air requirement for solid fuel combustion is calculated, the stoichiometric ratio of constituents and oxygen is considered by weight whereas for combustion of gaseous fuel the stoichiometric ratio by volume is considered.

2. When conditions at which combustion is carried out, are not mentioned the temperature and pressure are considered as 273^0K (0^0C) and 760 mm (1 atm) respectively.

3. At 273^0K (0^0C) and 760 mm (1 atm) – Air contains 23% oxygen by weight and 21% oxygen by volume

4. At 273^0K (0^0C) and 760 mm (1 atm) –

	1 g mole of any gas	= 22400 cm^3	= 22.4 L	= 22.4 dm^3
OR	1 kg mole of any gas	= 22400 X 1000 cm^3		
i.e.	1 kg mole of any gas	= 22.4 m^3		

Numerical 4

A solid fuel has C= 80%, H = 12%, S = 1%, N = 1%, Moisture = 1%, O = 5%. Calculate the volume of air required at 20^0C and 750mm pressure for complete combustion of 1 kg of fuel. (Molecular weight of air = 28.94)

Solution:

C + O2 ----> CO2	H2 + 1/2 O2 ----> H2O	S + O2 ----> SO2
12 32	2 16	32 32
0.8 ---- 2.13 kg	0.12 ---- 0.96 kg	0.01 ----- 0.01 kg

Total amount of oxygen required = 2.13 + 0.96 + 0.01 = 3.10 kg

Net amount of oxygen required = 3.10 – 0.05 = 3.05 kg

Air contains 23% oxygen by weight,

Amount of air required = (3.05) X 100/23 = 13.26 kg

For air, 28.94 = 22.4 m^3

Therefore, 13.26 kg = 13.26 X (22.4/28.97) m^3 = 10.26 m^3 ----- (at 273^0K and 760 mm pressure)

At given temp & pressure, Volume of air can be calculated by, $P_1V_1/T_1 = P_2V_2/T_2$ ---- (Temp in degree Kelvin)

Therefore volume of air required at given temp & pressure = V_2 = (760 x 10.26) X 293/(273 X 750)

=11.16 m^3

Numerical 5

Calculate volume of air required for complete combustion of $1m^3$ of fuel containing CH_4 = 35%, CO = 15%, H_2 = 40%, N_2 = 5% and O_2 = 5%

Solution:

Constituent	% by volume	volume per m^3
CH4	35	0.35
CO	15	0.15
H2	40	0.40
O2	5	0.05

CH4 + 2O2 ---> CO2 + 2H2O

1 vol 2vol

0.35 m3 ---- 0.7 m3

CO + 1/2O2 ---> CO2

1vol 0.5vol

0.15 m3 ----0.075 m3

H2 + 1/2 O2 ---> H2O

1vol 0.5vol

0.40 m3 ---- 0.20 m3

Total volume of oxygen required = 0.70 + 0.075 + 0.20 = 0.975 m3

Net amount of oxygen required = 0.975 – 0.05 = 0.925 m3

Air contains 21% oxygen by volume,

Volume of air required = (0.925) X 100/21

= 4.40 m3

Numerical 6

Calculate volume and weight of air required for complete combustion of 1m^3 of fuel containing CH_4 = 35%, CO = 15%, H_2 = 40%, N_2 = 5% and O_2 = 5%. (Mol. Weight of air = 28.94)

Solution:

Constituent	% by volume	volume per m^3
CH4	35	0.35
CO	15	0.15
H2	40	0.40
O2	5	0.05

CH4 + 2O2 ---> CO2 + 2H2O

1 vol 2vol

0.35 m3 ---- 0.7 m3

CO + 1/2O2 ---> CO2

1vol 0.5vol

0.15 m3 ----0.075 m3

H2 + 1/2 O2 ---> H2O

1vol 0.5vol

0.40 m3 ---- 0.20 m3

Total volume of oxygen required = 0.70 + 0.075 + 0.20 = 0.975 m3

Net amount of oxygen required = 0.975 – 0.05 = 0.925 m3

Air contains 21% oxygen by volume,

Volume of air required = (0.925) X 100/21 = 4.40 m3

For air, 22.4 m^3 = 28.94

Therefore, 4.40 m3 = 4.40 X (28.94/22.4) kg = 5.69 kg

Numerical 7

Calculate volume of air required at 25^0C and 730 mm pressure for complete combustion of $1m^3$ of fuel containing CH_4 = 35%, CO = 15%, H_2 = 40%, N_2 = 5% and O_2 = 5% if air contains 20% oxygen at this given temp & pressure

Solution:

Constituent	% by volume	volume per m^3
CH4	35	0.35
CO	15	0.15
H2	40	0.40
O2	5	0.05

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

1vol 2vol

0.35 m3 ---- 0.7 m3

$CO + 1/2 O_2 \rightarrow CO_2$

1vol 0.5vol

0.15 m3 ----0.075 m3

$H_2 + 1/2\ O_2 \rightarrow H_2O$

1vol 0.5vol

0.40 m3 ---- 0.20 m3

Total volume of oxygen required = 0.70 + 0.075 + 0.20 = 0.975 m3

Net amount of oxygen required = 0.975 – 0.05 = 0.925 m3

At given temp & pressure, Volume of oxygen can be calculated by, $P_1V_1/T_1 = P_2V_2/T_2$ ---- (Temp in degree Kelvin)

Therefore volume of oxygen required at given temp & pressure = V_2 = (760 x 0.925) X 298/(273 X 730)

= $1.051\ m^3$

At given temp and pressure air contains 20% oxygen,

Volume of air required at given temp and pressure = 1.051 X 100/20 m3

= 5.256 m3

Numerical 8

Calculate volume of air required at 25^{0}C and 730 mm pressure for complete combustion of 1m^3 of fuel containing C_2H_4 = 35%, CO = 15%, H_2 = 40%, N_2 = 5% and O_2 = 5% if air contains 20% oxygen at this given temp & pressure

Solution:

Constituent	% by volume	volume per m^3
C2H4	35	0.35
CO	15	0.15
H2	40	0.40
O2	5	0.05

C2H4 + 3O2 ---> 2CO2 + 2H2O

1 vol 3vol

0.35 m3 ---- 1.05 m3

CO + 1/2O2 ---> CO2

1vol 0.5vol

0.15 m3 ----0.075 m3

H2 + 1/2 O2 ---> H2O

1vol 0.5vol

0.40 m3 ---- 0.20 m3

Total volume of oxygen required = 1.05 + 0.075 + 0.20 = 1.325 m3

Net amount of oxygen required = 1.325 – 0.05 = 1.275 m3

At given temp & pressure, Volume of oxygen can be calculated by, $P_1V_1/T_1 = P_2V_2/T_2$ ---- (Temp in degree Kelvin)

Therefore volume of oxygen required at given temp & pressure = V_2 = (760 x 1.275) X 298/(273 X 730)

= 1.449m^3

At given temp and pressure air contains 20% oxygen,

Volume of air required at given temp and pressure = 1.449X 100/20 m3

= 7.245 m3

Numericals for practice

1. Calculate weight & volume of air required for complete combustion of 5 m3 of gaseous fuel which possesses by volume H_2 = 50%, CH_4 = 30%, N_2 = 2%, CO = 7%, C_2H_4 = 3% , C_2H_6 = 5% and Water Vapour = 3%. (Mol. Wt. of air = 28.94)
2. Calculate weight and volume of air required for complete combustion of 5 kg of carbon if 25% excess air is supplied. (Mol. Wt. of air = 28.949)
3. Calculate volume of air required at 27^0C and 730 mm pressure for complete combustion of $10m^3$ of fuel containing CH_4 = 30%, C_3H_8 = 20%, CO = 20%, H_2 = 25%, N_2 = 1% and O_2 = 2% if air contains 20% oxygen at this given temp & pressure.
4. Calculate volume and weight of air required for complete combustion of $1m^3$ of fuel containing ethane = 35%, isobutane = 15%, H_2 = 40%, N_2 = 5% and O_2 = 5%. (Mol. Weight of air = 28.94)
5. Calculate volume of air required at 25^0C and 1 atm pressure for complete combustion of $5m^3$ of fuel containing acetylene = 35%, CO2 = 15%, H_2 = 40%, water vapour = 5% and O_2 = 5%.