Unit 4: Fuels

Engineering Chemistry — DI01000071

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April 2, 2026

Unit 4 covers the chemistry of fuels — their classification, calorific value, analysis, and types of solid/liquid/gaseous fuels. Topics include Dulong's formula, coal analysis, petroleum fractions, and combustion calculations.

Unit 4 — Topics and Weightage

Topics at a Glance

#	Topic	Key Concepts
1	Classification of Fuels	Natural, artificial, solid/liquid/gas
2	Calorific Value	GCV, NCV, formula
3	Dulong's Formula	Calculation of GCV from composition
4	Solid Fuels: Coal	Types, proximate, ultimate analysis
5	Coal Products	Coke, coal gas, coal tar
6	Petroleum	Origin, fractions, cracking
7	Gaseous Fuels	Natural gas, LPG, water gas, producer gas
8	Combustion	Air/fuel ratio, flue gas analysis
9	Numericals	GCV, NCV, Dulong, combustion air

Weightage: $\approx$14% | GTU pattern: 2 $\times$ 7-mark + short answers

Fuels — Definition and Classification

Definition

A **fuel** is any substance which, when burned in air (O_2), produces heat energy economically, without harmful products in large quantities.

Basis	Type	Examples
Origin	Natural	Wood, coal, natural gas, petroleum
Origin	Artificial/Derived	Coke, LPG, coal gas, diesel
State	Solid	Wood, coal, coke, peat, charcoal
State	Liquid	Petrol, diesel, kerosene, ethanol
State	Gas	Natural gas, LPG, producer gas
Application	Primary	Used as obtained from nature
Application	Secondary	Processed/derived from primary

Calorific Value (CV)

Definition

Calorific value: Heat released per unit mass/volume of a fuel on complete combustion.

Units: kJ/kg (solid/liquid)   kJ/m^3 (gaseous fuels)

GCV (HCV)

Gross Calorific Value (Higher CV) Heat evolved when all combustion products including water are condensed to liquid.

NCV (LCV)

Net Calorific Value (Lower CV) Heat evolved when water in combustion products remains as steam (not condensed).

$\text{NCV} = \text{GCV} - 2442 \times m_w$ where m_w = mass of water formed per kg of fuel (kg/kg)

GCV–NCV Relationship and Formula

Relationship

NCV = GCV − latent heat of steam formed

If H = mass fraction of hydrogen in fuel:

Water formed per kg fuel = $9H$ kg
Latent heat of steam = 2442 kJ/kg (at 15°C)

$\boxed{\text{NCV} = \text{GCV} - 9H \times 2442}$ (all in kJ/kg)

Solved Example

A fuel has 15% H. GCV = 48000 kJ/kg. Find NCV.

Water = $9 \times 0.15 = 1.35$ kg
Latent heat = $1.35 \times 2442 = 3297$ kJ
NCV = $48000 - 3297 =$ **44703 kJ/kg**

Dulong's Formula for GCV

Dulong's Formula

$$\text{GCV} = 33800\,C + 144000\left(H - \frac{O}{8}\right) + 9390\,S \quad \text{kJ/kg}$$

where $C, H, O, S =$ mass fractions (from ultimate analysis)

Explanation of Terms

$33800\,C$	Heat from combustion of carbon
$144000(H-O/8)$	Net heat from H (subtracting H already combined with O and not available for burning)
$9390\,S$	Heat from combustion of sulfur

Dulong's Formula — Solved Numerical

Problem Statement

Coal: C = 75%, H = 5%, O = 12%, S = 2%, N = 3%, Ash = 3%.
Find GCV and NCV. (Latent heat of steam = 2442 kJ/kg)

Solution

Using Dulong's formula:

$$GCV = 33800(0.75) + 144000\left(0.05 - \frac{0.12}{8}\right) + 9390(0.02)$$

$$= 25350 + 144000(0.05 - 0.015) + 187.8$$

$$= 25350 + 5040 + 187.8 = \mathbf{30577.8\ kJ/kg}$$

Water formed $= 9 \times 0.05 = 0.45$ kg
NCV $= 30577.8 - 0.45 \times 2442 = 30577.8 - 1098.9 = \mathbf{29478.9\ kJ/kg}$

Solid Fuels — Coal: Formation and Types

Formation of Coal (Coalification)

Buried plant material undergoes slow compression + chemical change over millions of years under high pressure and temperature.

Peat $\rightarrow$ **Lignite** $\rightarrow$ **Sub-bituminous** $\rightarrow$ **Bituminous** $\rightarrow$ **Anthracite**

Type	C %	GCV kJ/kg	Properties
Peat	60	15000	Youngest; high moisture
Lignite	65–70	20000	Brown coal; soft
Bituminous	75–85	32000	Most common; caking
Anthracite	92–95	36000	Hardest; highest C; least smoke

Proximate Analysis of Coal

What is Proximate Analysis?

Routine test to determine **moisture**, **volatile matter**, **ash**, and **fixed carbon** content (all in %) by simple heating tests.

Parameter	Method	Significance
Moisture	Heat at 110°C for 1h	Reduces GCV; transport problem
Volatile matter	950°C in closed crucible	Determines smoke, ease of ignition
Ash	700°C in open crucible	Residue; reduces efficiency
Fixed carbon	100 - (M + VM + Ash)	Main heat-giving component

Good coal: High fixed carbon, low moisture, low ash, moderate volatile matter

Ultimate Analysis of Coal

What is Ultimate Analysis?

Chemical (elemental) analysis of coal to determine **C, H, N, S, O, Ash** by specialized analytical methods. Used to calculate GCV using Dulong's formula.

Element	Typical %	Significance
C	50–95%	Primary heat-producing element
H	2–6%	High heat; contributes to NCV loss
S	0.5–3%	Causes acid rain, equipment corrosion
N	1–3%	Gas fuel only; NO_x on combustion
O	2–20%	Reduces effective H; reduces GCV
Ash	2–25%	Inert; handling/disposal problem

Proximate vs Ultimate Analysis

Feature	Proximate	Ultimate
What is determined	M, VM, Ash, FC	C, H, N, S, O, Ash
Apparatus	Muffle furnace	Specialized analyzers
Time required	Few hours	More time
Cost	Low	High
Use	Routine quality control	GCV calculation, detailed study
Gives GCV directly?	No	Yes (Dulong's formula)

GTU Exam tip: Both types are 7-mark questions. Proximate: explain each *step+calculation*. Ultimate: explain *each element significance + Dulong formula*.

Coal Products — Carbonization

What is Carbonization?

Carbonization: Destructive distillation of coal in the *absence of air* to give coke, coal tar, and coal gas.

LTC (Low-Temp, 500–700°C)

- Soft coke (smokeless domestic fuel)
- More tar (more light oil)
- Less gas

HTC (High-Temp, 900–1200°C)

- Hard coke (metallurgical)
- More gas (coal gas)
- Less tar (more heavy oil)

Products: **Coke** (solid) + **Coal tar** (liquid, for chemicals) + **Coal gas** (fuel gas) + **Ammonia liquor**

Coke — Properties and Uses

Coke Properties

Coke is the solid residue left after carbonization. It is mainly carbon (90–95%) with very low volatile matter.

Properties

- Grey, porous, hard
- High carbon content ($\sim$92%)
- Low moisture, low ash
- GCV $\approx$ 29000–33000 kJ/kg
- Burns without smoke (low VM)

Uses

- **Metallurgy:** Blast furnace (iron making)
- **Fuel:** Household heating
- **Reducing agent:** Metal extraction
- **Electrode manufacture:** Graphite electrodes

Coal Gas — Composition and Uses

What is Coal Gas?

Gas produced as byproduct of HTC of coal. *Calorific value $\approx$ 20000 kJ/m^3*

Composition

Component	**Approx %**
H_2	50–54%
CH_4	30–35%
CO	6–8%
CnHm	2–4%
N_2, CO_2	Balance

Uses

- Domestic/industrial fuel
- Formerly used as town gas in pipelines
- Chemical feedstock (H_2)
- WARNING: Toxic (contains CO)

Petroleum — Origin, Composition

Origin

Crude petroleum formed from marine organisms buried over millions of years under high pressure; *complex mixture of hydrocarbons (alkanes, cycloalkanes, aromatics) + sulfur/N/O compounds*.

Composition

C	80–90%
H	10–14%
S	0.1–3%
N	0.1–2%
O	up to 2%

Hydrocarbon Types

- Paraffins (alkanes)
- Naphthenes (cycloalkanes)
- Aromatics
- Small amount alkenes/alkynes

Fractional Distillation of Petroleum

Process

Crude petroleum heated to $\sim$400°C; vapours pass into fractionating column; different fractions condense at different levels based on boiling point.

Fraction	B.P. ($^\circ$C)	Uses
Refinery gas	< 20	LPG, fuel gas
Gasoline/Petrol	20–70	Fuel for cars
Naphtha	70–120	Solvent, chemical feedstock
Kerosene	150–250	Jet fuel, heating
Diesel oil	250–350	Diesel engines
Fuel oil	350–400	Furnaces, ships
Lubricating oil	$>$400	Lubrication
Bitumen/Asphalt	Residue	Road paving, waterproofing

Cracking of Petroleum

Definition

Cracking: Breaking down of large, heavy hydrocarbon molecules into smaller, more useful ones (especially petrol-range C_5–C_{12}) by heat, pressure, or catalysts.

Thermal Cracking

500–700°C, 10–70 atm
No catalyst
Gives more alkenes
Used for ethylene production

Catalytic Cracking

500°C, lower pressure
Catalyst: zeolite or silica-alumina
Gives more branched alkanes (high octane)
Preferred for petrol production

Example: $C_{16}H_{34} \xrightarrow{\text{cat/heat}} C_8H_{18} + C_8H_{16}$

Knocking and Octane Number

Knocking

Knocking (pinking): Premature auto-ignition of fuel-air mixture in SI engine before spark; causes metallic noise and reduces engine efficiency/life.

Octane Number (ON)

Measure of anti-knock quality of petrol.
ON defined: % iso-octane in a blend of iso-octane (ON=100) and n-heptane (ON=0) that gives same knock as the fuel sample.

Higher ON = less knocking tendency.

Increase ON by: Catalytic cracking | Isomerization | Adding additives (earlier: TEL; now: ethanol, MTBE) | Blending with aromatics

Cetane Number and Diesel Quality

Cetane Number (CN)

Measure of ignition quality of **diesel fuel** in a CI (compression ignition) engine.

CN defined: % cetane (hexadecane, CN=100) in blend with α-methyl naphthalene (CN=0) with same ignition delay as fuel.

Higher CN = **shorter ignition delay** = **better diesel quality**

Feature	Octane vs Cetane
Engine type	SI (spark ignition) vs CI (compression ignition)
Fuel	Petrol / gasoline vs Diesel
High number means	Anti-knock (ON) vs Easy ignition, short delay (CN)
Typical value	Petrol: ON $\approx$ 87–95 vs Diesel: CN $\approx$ 45–55

Gaseous Fuels — Overview

Advantages of Gaseous Fuels

- High calorific value per kg
- No ash or smoke
- Easily piped/transported
- Easy, complete combustion
- Easy ignition and control
- Uniform composition

Fuel	**GCV kJ/m^3**	**Main Components**
Natural gas	37000–40000	CH_4 (85%), C_2H_6, CO_2
LPG	93000–97000	Propane (C_3H_8) + Butane (C_4H_{10})
Coal gas	18000–20000	H_2, CH_4, CO
Producer gas	4600–5400	CO, N_2, CO_2, H_2
Water gas	11000–12000	CO (50%), H_2 (45%)
Biogas	21000–25000	CH_4 (60%), CO_2

Natural Gas and LPG

Natural Gas

- Found with petroleum deposits
- **Main:** CH_4 (85–90%)
- Also: C_2H_6, C_3H_8, CO_2, N_2
- GCV ≈ 37000 kJ/m^3
- Burns cleanly (CNG for vehicles)
- Transported in pipelines or as LNG

LPG (Liquefied Petroleum Gas)

- Mixture of propane (C_3H_8) and butane (C_4H_{10})
- Stored as liquid under pressure
- Odorant (ethyl mercaptan) added
- GCV ≈ 46000 kJ/kg
- **Domestic:** cooking gas
- **Industrial:** heating, autogas

Producer Gas and Water Gas

Producer Gas

Made by: Blowing air through hot coke bed

$2C + O_2 \rightarrow 2CO$
$C + CO_2 \rightarrow 2CO$

Composition: CO 25%, N_2 65%, CO_2 4%, H_2 4%
GCV: $\approx$5000 kJ/m^3 (low)
Uses: Industrial furnaces, not domestic

Water Gas

Made by: Blowing steam through red-hot coke

$C + H_2O \rightarrow CO + H_2$
$CO + H_2O \rightarrow CO_2 + H_2$

Composition: CO 45%, H_2 50%
GCV: $\approx$11600 kJ/m^3
Uses: Fuel, H_2 source

Biogas

What is Biogas?

Gas produced by **anaerobic decomposition** of organic matter (animal dung, agricultural waste, sewage) by methanogenic bacteria.

Composition

CH_4: 55–65%
CO_2: 30–40%
H_2S, N_2, H_2: Small amounts

GCV $\approx$ 22000 kJ/m^3

Advantages

- Renewable; reduces waste
- Low pollution
- Slurry = excellent manure
- Cheap for rural areas
- Reduces deforestation

Combustion of Fuels

Definition

Combustion: Rapid oxidation of a fuel releasing heat and light. Requires fuel, oxygen, and ignition temperature.

Key Combustion Reactions

$C + O_2 \rightarrow CO_2 + 393.5$ kJ
$2H_2 + O_2 \rightarrow 2H_2O + 483$ kJ
$S + O_2 \rightarrow SO_2 + 296$ kJ
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 890$ kJ
$2CO + O_2 \rightarrow 2CO_2 + 566$ kJ

Incomplete combustion: Insufficient $O_2 \Rightarrow CO$ (toxic) formed instead of CO_2. $2C + O_2 \rightarrow 2CO$

Theoretical Air Requirement for Combustion

Formula (Stoichiometric Air)

Minimum air required (by mass) per kg of fuel for complete combustion:

$$\text{Air req.} = \frac{100}{23.2}\left[2.67\,C + 8\,H + S - O\right] \text{ kg air/kg fuel}$$

where $C, H, S, O =$ mass fractions; Air contains 23.2% O_2 by mass.

Derivation Idea

From stoichiometry:
1 kg C needs 8/3 kg O_2; 1 kg H needs 8 kg O_2; 1 kg S needs 1 kg O_2.
Subtract O_2 already in fuel. Divide by 0.232 to get air.

Theoretical Air — Solved Numerical

Problem

Ultimate analysis of fuel: C 85%, H 12%, S 1%, O 2%. Find theoretical air required per kg of fuel.

Solution

O_2 required $= 2.67(0.85) + 8(0.12) + 1(0.01) - 0.02$

$= 2.270 + 0.960 + 0.010 - 0.020 = 3.22$ kg O_2/kg fuel

Air required $= \dfrac{3.22}{0.232} =$ **13.88 kg air/kg fuel**

Excess air % used in practice = 20–40% above stoichiometric

Flue Gas Analysis — Orsat Apparatus

Principle

Flue gas (combustion products) analyzed volumetrically by absorbing each component:

Step	Absorbent	Gas absorbed	Result
1	KOH solution (33%)	CO_2	% CO_2
2	Pyrogallol + KOH	O_2	% O_2
3	$CuCl/NH_4Cl$ (amm. cuprous chloride)	CO	% CO
4	Remainder	N_2	% N_2 by diff.

Use: Determine combustion efficiency; check for excess air or incomplete combustion
Good combustion: CO_2 high, $CO \approx 0$, O_2 low

PYQ — 7-Mark Questions: Unit 4 Fuels

Frequently Asked

1. Explain proximate analysis of coal with procedure and significance. [7]
2. Explain ultimate analysis of coal and its significance. [7]
3. What is Dulong's formula? Calculate GCV and NCV with given analysis. [7]
4. Explain fractional distillation of petroleum with fractions and uses. [7]
5. Explain cracking of petroleum (thermal and catalytic). [7]
6. Explain Orsat apparatus with neat diagram and procedure. [7]
7. Define knocking. Explain octane number and cetane number. [7]
8. Explain LPG and biogas: composition, preparation, uses. [7]

Unit 4 — Numericals Practice Bank

1. Coal: C 70%, H 6%, O 10%, S 2%, Ash 12%. Find GCV and NCV.
2. A fuel has GCV = 50000 kJ/kg, H = 14%. Find NCV.
3. Coal: C 78%, H 5%, O 8%, S 1.5%, N 1%, Ash 6.5%. Find GCV by Dulong's formula.
4. Fuel: C 88%, H 10%, S 0.5%, O 1.5%. Find theoretical air required per kg of fuel.
5. NCV of a fuel = 42000 kJ/kg; H = 11%. Find GCV.
6. Proximate analysis: M=5%, VM=32%, Ash=8%. Find fixed carbon. % and comment on fuel quality.

Unit 4 — Midpoint Summary

Topic	Key Point
Classification	Solid/Liquid/Gas; Natural/Artificial
GCV vs NCV	GCV = water condensed; NCV = water as steam
Dulong's formula	GCV = 33800C + 144000(H-O/8) + 9390S
Coal types	Peat < Lignite < Bituminous < Anthracite (rank order)
Proximate analysis	M, VM, Ash, FC — by heating
Ultimate analysis	C, H, N, S, O, Ash — elemental; used for Dulong
Petroleum fractions	8 fractions from refinery gas to bitumen
Cracking	Thermal: high temp; Catalytic: zeolite (better quality)
Octane/Cetane	ON for petrol (anti-knock); CN for diesel (easy ignition)
Producer gas	Low GCV ($CO + N_2$); Water gas: High GCV ($CO + H_2$)

Reforming of Petroleum

Definition

Reforming: Conversion of low-octane straight-chain hydrocarbons into high-octane branched/aromatic ones *without* changing molecular weight. Uses Pt/Re catalyst at 500°C, 15–35 atm (**catalytic reforming**).

Key Reactions

n-hexane $\rightarrow$ 2-methylpentane	Isomerization
Cyclohexane $\rightarrow$ benzene + $3H_2$	Dehydrogenation
n-heptane $\rightarrow$ toluene + $4H_2$	Aromatization

Result: High-octane reformate used directly in petrol; H_2 byproduct used in hydrotreating.

Synthetic Petrol — Fischer-Tropsch Process

Fischer-Tropsch Synthesis

Production of liquid hydrocarbons (synthetic petrol) from **syngas** ($CO + H_2$) using Fe or Co catalyst at 150–300°C.

$$n\,CO + (2n+1)\,H_2 \xrightarrow{\text{Fe/Co}} C_nH_{2n+2} + n\,H_2O$$

Bergius Process (Hydrogenation of Coal)

$$\text{Coal} + H_2 \xrightarrow{400^\circ\text{C, 200 atm, Fe catalyst}} \text{liquid hydrocarbons (synthetic petrol)}$$

Used in Germany during WWII; important for coal-rich/oil-poor nations.

Gasoline Quality and Anti-Knock Additives

Why Additives?

Straight-run petrol from distillation has ON $\approx$ 60–70. Modern engines require ON $\geq$ 87. Additives/processes raise ON.

Additive/Process	Note
TEL (tetraethyl lead)	Historically used; banned now (toxic Pb pollution)
MTBE	Methyl tert-butyl ether; oxygenate; phased out in USA
Ethanol blending	E10, E20 blends; renewable; common today
Aromatics addition	Benzene, toluene raise ON; limited for health reasons
Catalytic reforming	Best industrial method; produces high-ON reformate
Isomerization	n-butane $\rightarrow$ isobutane; $\uparrow$ON without aromatics

Fuel Combustion and Air Pollution

Major Pollutants from Fuel Combustion

Pollutant	Source	Effect
CO	Incomplete combustion	Haemoglobin binds; asphyxiation
CO_2	All combustion	Greenhouse gas, climate change
SO_2	S in coal/oil	Acid rain, respiratory problems
NO_x	High-temp combustion	Smog, acid rain
Particulates	Coal, heavy oil	Lung damage
HC vapours	Engine blowby	Smog precursor (photochemical)

Mitigation: Catalytic converters | Flue gas desulfurization | LNG/CNG use | EGR (exhaust gas recirculation) | High-efficiency combustion

Calorific Value of Gaseous Fuels — Calculation

Method for Gaseous Fuels

GCV of a gaseous fuel mixture $= \sum$ (mole fraction $\times$ GCV of component)

Alternatively, use combustion enthalpy of each component from standard values.

Solved Example

Coal gas composition (by volume): H_2 52%, CH_4 33%, CO 8%, CO_2 3%, N_2 4%

GCV of $H_2 = 12770$, $CH_4 = 35880$, $CO = 12630$ kJ/m^3

$\text{GCV} = 0.52 \times 12770 + 0.33 \times 35880 + 0.08 \times 12630 + 0 + 0$

$= 6640 + 11840 + 1010 =$ **19490 kJ/m^3**

Excess Air and Combustion Efficiency

Why Use Excess Air?

Theoretical air is minimum; in practice **20–50% excess air** is supplied to ensure complete combustion and avoid CO formation.

Too Little Air

Incomplete combustion
CO formed (toxic)
Soot/smoke produced
Low heat release
Fuel wastage

Too Much Excess Air

Excess N_2 heated unnecessarily
Heat carried away in flue gas
Lower thermal efficiency
Excessive NO_x at high temp

Optimum: Orsat analysis guides control — aim for CO_2 max, CO $\approx$ 0.

Renewable and Alternative Fuels

Fuel	Source/Production	Advantages
Biogas	Anaerobic digestion	Renewable; waste utilization
Ethanol	Fermentation of sugars	Blended with petrol; lower CO
Biodiesel	Transesterification of oils	Blended with diesel; biodegradable
Hydrogen	Electrolysis / steam reforming	Zero CO_2 at point of use
Syngas	Coal/biomass gasification	Flexible feedstock
Methanol	$CO + 2H_2$ (from biomass)	Liquid; high ON (115)

India: National Biofuel Policy mandates 20% ethanol blending (E20) by 2025; PM-JIVANyojana for 2G ethanol from bagasse.

Numerical — Flue Gas Analysis

Problem

Flue gas analysis by Orsat: $CO_2 = 12\%$, $O_2 = 6\%$, $CO = 2\%$, $N_2 = 80\%$. Fuel: C 85%, H 10%, S 0%, O 5%. Find theoretical air per kg fuel and % excess air.

Solution

Theoretical $O_2 = 2.67(0.85) + 8(0.10) - 0.05 = 2.27 + 0.80 - 0.05 = 3.02$ kg
Theoretical air $= 3.02/0.232 = 13.02$ kg

$$\text{Excess air } \% = \frac{\%O_2 - \frac{1}{2}\%CO}{\%N_2} \times \frac{N_2 \text{ (of air)}}{O_2 \text{ (of air)}} \times 100$$

$$\text{Simplified: } \approx \frac{6-1}{80} \times \frac{79}{21} \times 100 \approx \mathbf{23.6}\%$$

Coal Tar — Fractions and Uses

What is Coal Tar?

Black, viscous liquid byproduct of HTC of coal. Contains >300 organic compounds (benzene, toluene, naphthalene, anthracene, phenol, etc.).

Fraction	B.P. ($^\circ$C)	Products/Uses
Light oil	$<$170	Benzene, toluene, xylene (solvents)
Middle oil	170–230	Phenol, cresol (disinfectants), naphthalene
Heavy oil	230–270	Naphthalene (mothballs), basic dyes
Anthracene oil	270–360	Anthracene (dyes), phenanthrene
Pitch	$>$360	Road making, waterproofing, electrodes

Comparison of Industrial Gaseous Fuels

Feature	Coal Gas	Producer	Water Gas	Natural Gas
Source	HTC coal	Air + coke	Steam + coke	Underground
CH_4 %	28–35	<1	0	85
H_2 %	50	4	48	Trace
CO %	8	25	45	0
N_2 %	4	65	5	3
GCV kJ/m^3	18000	5000	11600	37000
Toxicity	Toxic (CO)	Very toxic	Toxic	Non-toxic

Bomb Calorimeter — GCV Measurement

Principle

Known mass of fuel burned with excess O_2 in sealed steel bomb immersed in a calorimeter. Heat released raises temperature of known mass of water.

$q = (m_w c_w + W) \times \Delta T$
where W = water equivalent of calorimeter, $m_w c_w$ = heat capacity of water.
$\text{GCV} = q/m_{\text{fuel}}$

Note: Bomb calorimeter gives **GCV** (water condensed at high pressure). Bomb calorimeter cannot give NCV directly.

Comparison of Solid, Liquid and Gaseous Fuels

Property	Solid	Liquid	Gaseous
GCV (kJ/kg)	15000–36000	42000–50000	High per kg
Handling	Difficult	Easy	Easiest (pipeline)
Storage	Easy, cheap	Easy (tanks)	Difficult (pressure)
Ignition	High temp	Easy	Easiest
Combustion control	Poor	Good	Best
Ash produced	Yes	No	No
Pollution	Most	Moderate	Least
Transport	Rail/road	Tanker/pipeline	Pipeline/cylinder

PYQ Short-Answer Practice (2-mark)

1. Define GCV and NCV. How are they related?
2. What is Dulong's formula? Name all terms.
3. Differentiate thermal and catalytic cracking.
4. Define octane number and cetane number.
5. What is knocking? How can it be reduced?
6. List four fractions of petroleum with their uses.
7. What is proximate analysis? Which heating steps are used?
8. What is producer gas? Give composition.
9. What is water gas? How is it prepared?
10. Define bomb calorimeter. What does it measure?
11. Why is excess air used in combustion?
12. Name the absorbents used in Orsat apparatus.

Exam Tips — Unit 4: Fuels

Do's

- Show full substitution in Dulong's formula
- Write combustion reactions for each element separately
- For proximate: state temperature and time at each step
- Remember: FC = 100 − (M + VM + Ash)
- For Orsat: state absorbents in correct order (CO_2 first)

Don'ts

- Don't confuse GCV and NCV (GCV $>$ NCV always)
- Don't forget to subtract O/8 in Dulong's formula
- Don't swap octane (petrol) and cetane (diesel)
- Don't forget to use mass fractions (not percent) in formulas
- Don't use 21% O_2 in mass-basis air calc — use 23.2%

Unit 4 — Revision Flash Points

Key Fact	Value / Rule
GCV kJ/kg (wood)	≈17000
GCV kJ/kg (coal)	25000–36000
GCV kJ/kg (petrol)	≈47000
GCV kJ/kg (diesel)	≈45000
Latent heat (steam)	2442 kJ/kg (used in NCV calc)
Air = 23.2% O_2	Mass basis for air calc
Orsat order	$CO_2 \rightarrow O_2 \rightarrow CO \rightarrow N_2$
Proximate: FC	FC = 100 − M − VM − Ash
Dulong formula	$33800C + 144000(H - O/8) + 9390S$
Cracking catalyst	Zeolite / silica-alumina (FCC)

Numerical Variations — GCV and NCV

Type 1: Find NCV from GCV

Fuel: GCV $= 35000$ kJ/kg, H $= 4\%$
NCV $=$ GCV $-9H \times 2442 = 35000 - 9(0.04)(2442)$
$= 35000 - 879.1 =$ **34120.9 kJ/kg**

Type 2: Find GCV from NCV

Fuel: NCV $= 42700$ kJ/kg, H $= 13\%$
GCV $=$ NCV $+9H \times 2442 = 42700 + 9(0.13)(2442)$
$= 42700 + 2857.1 =$ **45557.1 kJ/kg**

Tip: GCV is always greater than NCV for fuels containing hydrogen.

Proximate Analysis — Numerical

Problem

A coal sample gave: Initial mass = 2 g
After drying at 110°C: 1.92 g
After heating at 950°C (closed): 1.32 g
After heating at 700°C (open): 0.28 g
Find: M%, VM%, Ash%, FC%

Solution

$$\text{Moisture} = \frac{2 - 1.92}{2} \times 100 = \mathbf{4\%}$$

$$\text{VM} = \frac{1.92 - 1.32}{2} \times 100 = \mathbf{30\%}$$

$$\text{Ash} = \frac{0.28}{2} \times 100 = \mathbf{14\%}$$

$$\text{FC} = 100 - 4 - 30 - 14 = \mathbf{52\%}$$

Ultimate Analysis — Numerical (Dulong)

Problem

Ultimate analysis: C = 80%, H = 8%, S = 2%, N = 2%, O = 6%, Ash = 2%.
Find GCV and NCV.

Solution

$$GCV = 33800(0.80) + 144000\left(0.08 - \frac{0.06}{8}\right) + 9390(0.02)$$
$$= 27040 + 144000(0.08 - 0.0075) + 187.8$$
$$= 27040 + 144000(0.0725) + 187.8$$
$$= 27040 + 10440 + 187.8 = \mathbf{37668\ kJ/kg}$$
$$NCV = 37668 - 9(0.08)(2442) = 37668 - 1758 = \mathbf{35910\ kJ/kg}$$

Numerical — Theoretical Air (GTU Style)

Problem

Coal: C 75%, H 5%, S 2%, O 10%, N 5%, Ash 3%.
Find (a) theoretical air per kg fuel, (b) volume of air at STP per kg fuel.

Solution

O_2 needed $= 2.67(0.75) + 8(0.05) + 0.02 - 0.10$
$= 2.003 + 0.40 + 0.02 - 0.10 = 2.323$ kg O_2

(a) Air $= 2.323/0.232 =$ **10.01 kg/kg fuel**

(b) Volume at STP: mol $O_2 = 2.323/32 = 0.0726$ kmol
Air $= 0.0726/0.21 = 0.346$ kmol $= 0.346 \times 22.4 =$ **7.74 m^3/kg fuel**

Unit 4 — PYQ Pattern Analysis

Topic	May 23	Nov 23	May 24
Proximate analysis	7	–	7
Ultimate analysis + Dulong	7	7	–
GCV/NCV numerical	3	3	3
Cracking	–	7	7
Petroleum fractions	3	–	3
Gaseous fuels (LPG/Biogas)	–	3	–
Orsat apparatus	7	–	7
Octane/Cetane number	3	3	3
Air for combustion	3	3	–
Coal types	–	3	–

Most likely 7-mark: Proximate analysis **OR** Dulong numerical **OR** Orsat apparatus

Combustion Numericals — More Practice

1. Fuel: C 72%, H 4%, O 8%, S 1%, Ash 15%. Find GCV by Dulong's.
2. GCV $= 40000$ kJ/kg, H $= 16\%$. Find NCV.
3. Fuel: C 88%, H 9%, O 2%, S 1%. Find theoretical O_2 and air per kg.
4. If 30% excess air is used, find actual air per kg for above fuel.
5. Bomb calorimeter: m $= 0.9$ g fuel, $\Delta T = 2.5^\circ$C, water $= 2000$ g, W $= 500$ g. Find GCV.
6. Gaseous fuel: H_2 40%, CO 50%, N_2 10% (by vol). Find GCV (kJ/m^3).

Petroleum Refining — Complete Picture

Refinery Operations Summary

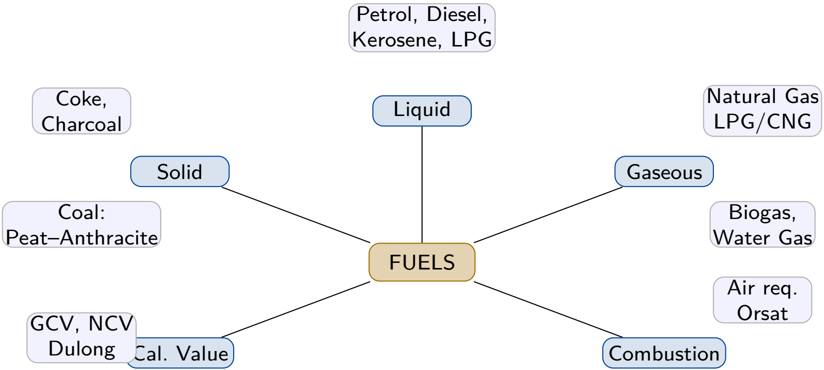
Process	Input $\rightarrow$ Output
Atmospheric distillation	Crude oil $\rightarrow$ LPG, petrol, kerosene, diesel, fuel oil
Vacuum distillation	Residue $\rightarrow$ lube oil, wax, bitumen
Thermal cracking	Heavy gas oil $\rightarrow$ alkenes (ethylene)
Catalytic cracking (FCC)	Heavy distillate $\rightarrow$ high-octane gasoline
Catalytic reforming	Naphtha $\rightarrow$ high-octane reformate + H_2
Hydrotreating	All fractions $\rightarrow$ desulfurized products
Isomerization	n-butane/pentane $\rightarrow$ high-octane isoalkanes

Flash Point, Fire Point and Self-Ignition Temperature

Property	Definition	Significance
Flash point	Lowest temp at which vapours momentarily ignite when flame is applied	Fire safety; storage classification
Fire point	Temp at which vapours sustain combustion for $\geq$5 s	More conservative safety limit
Self-ignition temp (SIT)	Temp at which fuel ignites without external flame	Engine knock; spontaneous fire risk

Typical values: Petrol FP $= -43^\circ$C (very flammable) | Diesel FP $= 52^\circ$C | Kerosene FP $= 38^\circ$C
Higher flash point = safer storage.

Unit 4 — Fuels Mind Map



Unit 4 — Key Formulas Summary

Formula	Variables
$GCV = 33800C + 144000(H - O/8) + 9390S$	C,H,O,S = mass fractions
$NCV = GCV - 9H \times 2442$	H = mass fraction
$\text{Air} = \dfrac{2.67C + 8H + S - O}{0.232}$	per kg fuel (mass basis)
$FC = 100 - M - VM - \text{Ash}$	All in %
$q = (m_w c_w + W)\Delta T$	Bomb calorimeter
$\text{GCV (gas)} = \sum x_i \cdot \text{GCV}_i$	x_i=vol. fraction

Coal vs Petroleum — Comparison

Feature	Coal	Petroleum
State	Solid	Liquid
Origin	Plant matter	Marine organisms
Main element	C (50–95%)	C+H (alkanes, cycloalkanes)
GCV (kJ/kg)	15000–36000	40000–50000
Sulfur content	0.5–3%	0.1–3%
Handling	Difficult	Easy
Combustion control	Poor	Good
Ash produced	Yes	No
Products of processing	Coke, tar, gas	Petrol, diesel, kerosene, LPG
Reserves (India)	Large	Limited

Environmental Impact of Fossil Fuels

Greenhouse Effect

Combustion of fossil fuels releases CO_2 (main GHG), CH_4 (natural gas leaks), and N_2O. These trap heat in the atmosphere, raising global temperatures (**global warming**).

Other Environmental Effects

Acid rain	$SO_2 + NO_x$ from coal/oil power plants
Photochemical smog	NO_x + VOC + sunlight (ozone, PAN)
Particulate pollution	Coal combustion, diesel engines
Oil spills	Tanker accidents; marine ecosystem damage

Hydrogen — The Future Fuel

Why Hydrogen?

High GCV	$\approx$143000 kJ/kg (highest of all fuels)
Zero CO_2 at use	$2H_2 + O_2 \rightarrow 2H_2O$ only
Renewable (if green)	Electrolysis using solar/wind power
Versatile	Fuel cells, IC engines, heating

Challenges

Storage (very low density gas; cryogenic or high-pressure tanks) | Production cost (green H_2 still expensive) | Safety (highly flammable, widest flammability range: 4–75% in air)

Unit 4 — Complete Summary Table

Topic	Core Outcome
Classification	Solid/liquid/gas; natural/artificial
GCV vs NCV	GCV $>$ NCV; diff $=$ latent heat of steam
Dulong's formula	GCV from elemental analysis (C, H, O, S)
Proximate analysis	M, VM, Ash, FC by stepwise heating
Ultimate analysis	Elemental %; used for Dulong
Petroleum fractions	8 fractions; fractional distillation
Cracking	Thermal (alkenes) vs Catalytic (high-ON petrol)
Octane/Cetane	ON for petrol; CN for diesel
Gaseous fuels	Natural gas (CH_4), LPG, biogas, producer/water gas
Orsat apparatus	$CO_2 \rightarrow O_2 \rightarrow CO \rightarrow N_2$; checks combustion efficiency

Unit 4 Complete — Bridge to Unit 5: Lubricants

Unit 4 in One Line

Fuels are substances that release heat on combustion; coal and petroleum are primary fossil fuels obtained by geological processes; their quality is measured by calorific value (Dulong's formula for solid/liquid, stoichiometry for gases); combustion efficiency is monitored by Orsat analysis.

Coming Next — Unit 5: Lubricants

Unit 5 covers **classification of lubricants** (liquid, semi-solid, solid), mechanisms of lubrication, essential properties (viscosity, flash/fire point, cloud/pour point, acid value, saponification number, aniline point), and their applications.