# *Fuel & Advanced Combustion*

## Lecture 1

## *Fuel (1)*

# Fuels

- Since the heat energy is derived from the fuel, a fundamental knowledge of the types of fuels and their characteristics is essential to understand the combustion phenomenon.

- The characteristics of fuel has a considerable influence on the design, efficiency, output and particularly the reliability and durability of the engine.

- Further, the fuel characteristics play an important role in the atmospheric pollution caused by the automobile engines.

# Fuels

- Internal combustion engines can be operated on different types of fuels such as
  - Liquid fuels
  - Gaseous fuels
  - Solid fuels

- The design of the engine usually depends upon the type of fuel used.

# Solid Fuels

- This type of fuel was used in early engines. During the initial stages of engine development, solid fuels (such as finely powdered coal) was used.

- However, due to the problem of handling the fuel as well as in disposing off the solid residue or ash (after combustion), solid fuels find little practical application today.

## Solid Fuels – contd.

- Further, there are storage and feeding problems associated with solid fuels as compared to gaseous and liquid fuels.

- However, attempts are being made to produce gaseous or liquid fuels from charcoal for their use in engines.

# Gaseous Fuels

- Gaseous fuels are ideal for internal combustion engines. They mix more homogeneously with air. However, their use is restricted in automobiles due their storage and handling problems.

- Gaseous fuels are suitable for stationary powerplants near the source of availability of the fuel. They can be liquefied under pressure to reduce the storage volume, but this process is very expensive and risky.

# Liquid Fuels

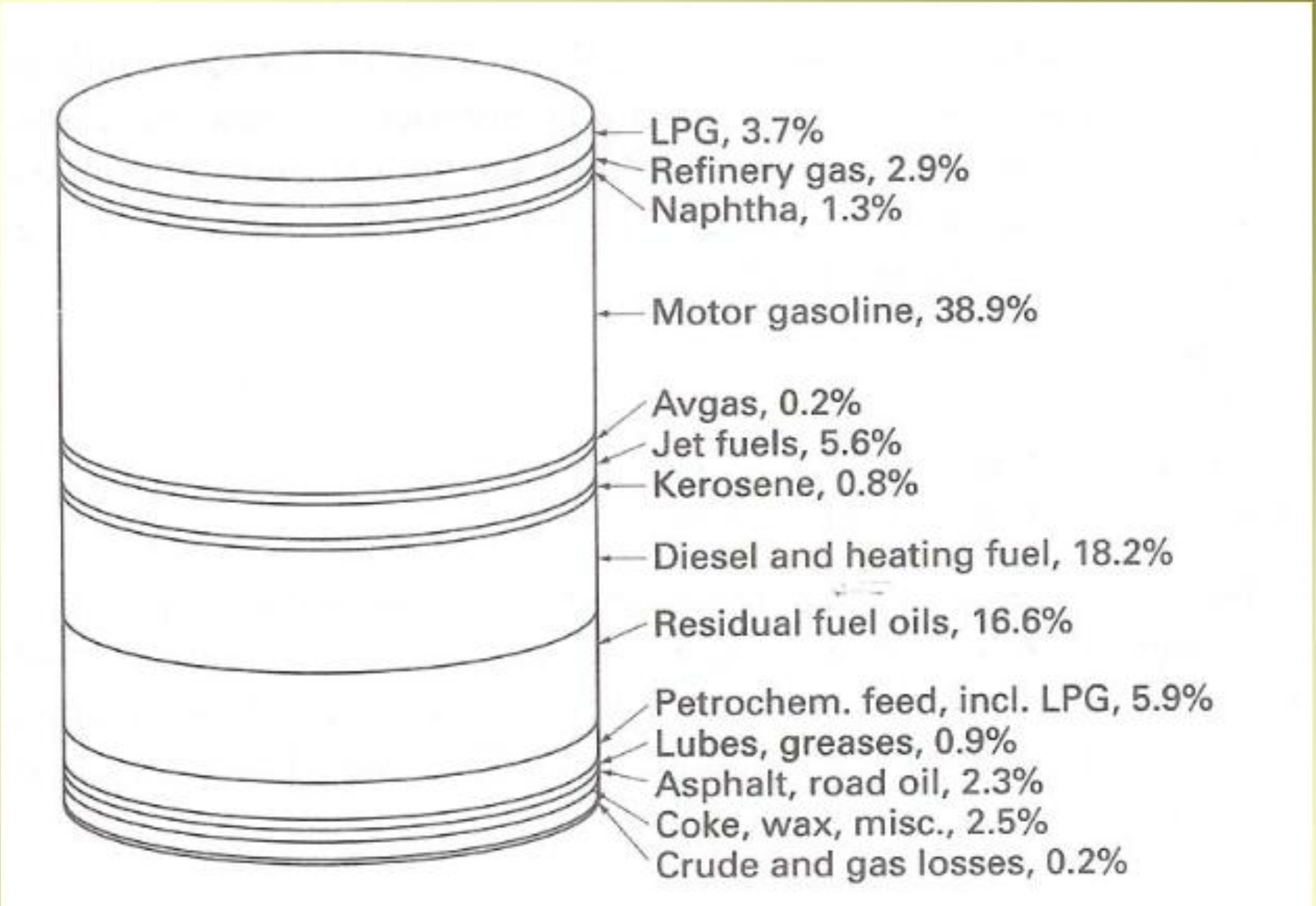
- The liquid fuels are mostly used in modern internal combustion engines. Basically, they are the derivatives of liquid petroleum. The commercial types are:

  - Benzyl
  - Alcohol
  - Petroleum products

# Petroleum

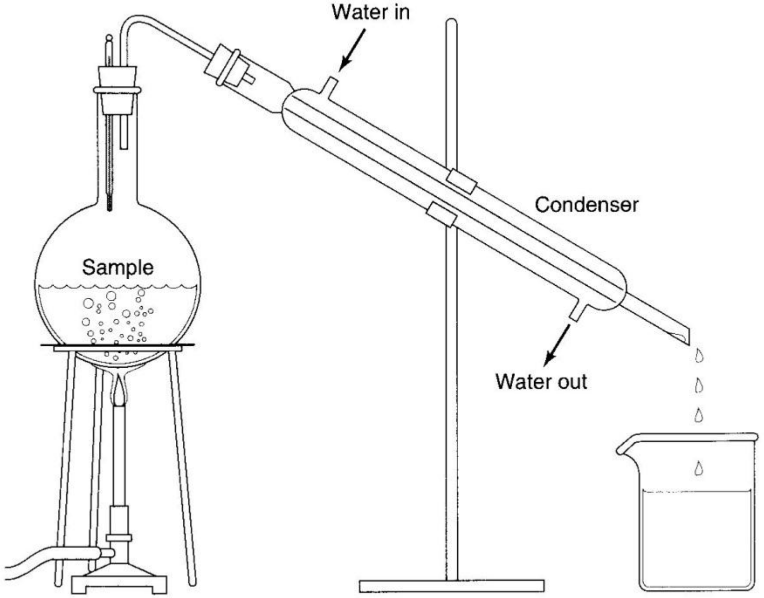
- Petroleum (obtained from crude oil) is a mixture of many hydrocarbons with varying molecular structure. It also contains small amounts of

  - Sulphur
  - Oxygen
  - Nitrogen
  - Impurities (such as water, sand etc.)

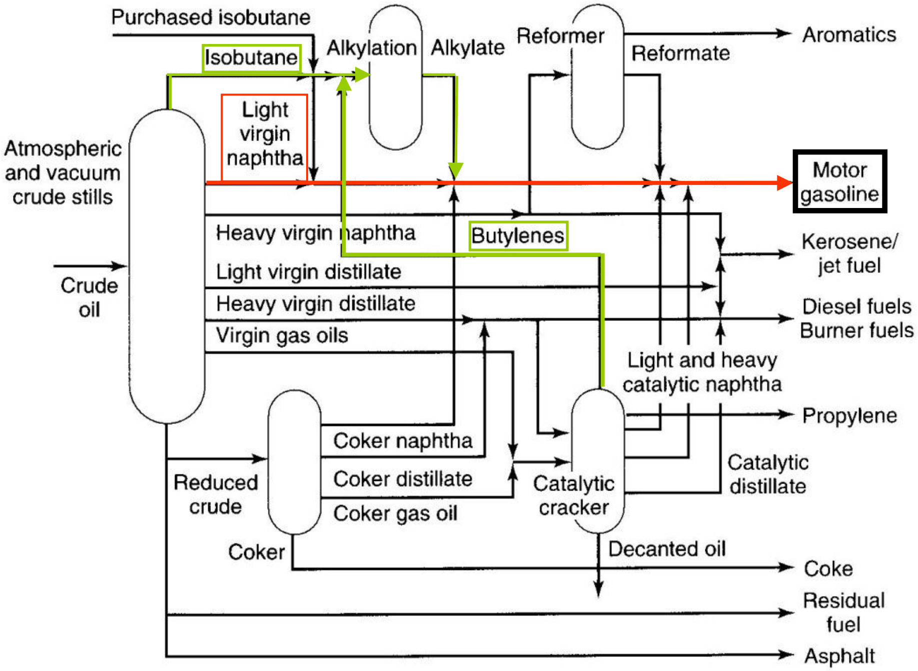



**Typical end products from crude oil. A single refinery produces some, but not all, of the products shown. The percentage refer to overall production from total refinery output.**

**Distillation Process**




**Refining Process**



# Petroleum

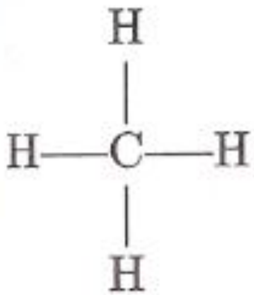
- The linking of hydrogen and carbon atoms (in different ways in a hydrocarbon molecule) influences the physical and chemical properties of different hydrocarbon groups.

- The carbon and hydrogen combine in different proportions and molecular structures to form a variety of hydrocarbons. Depending upon the number of carbon and hydrogen atoms, the petroleum products are classified into various groups.

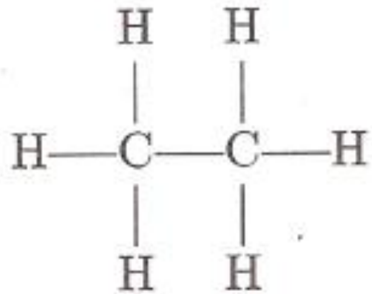
## Basic families of hydrocarbons

| Family of hydrocarbons | General formula | Molecular structure | Saturated/ Unsaturated | Stability |
|---|---|---|---|---|
| Paraffin | $C_nH_{2n+2}$ | Chain | Saturated | Stable |
| Olefin | $C_nH_{2n}$ | Chain | Unsaturated | Unstable |
| Naphthene | $C_nH_{2n}$ | Ring | Saturated | Stable |
| Aromatic | $C_nH_{2n-6}$ | Ring | Highly unsaturated | Most unstable |

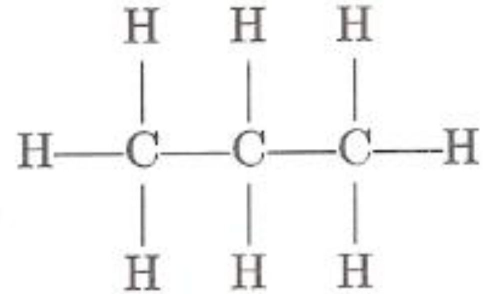
# Paraffin series



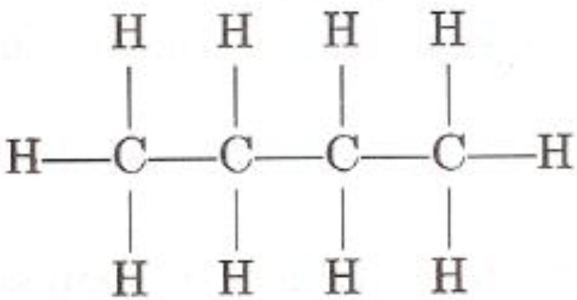
Methane



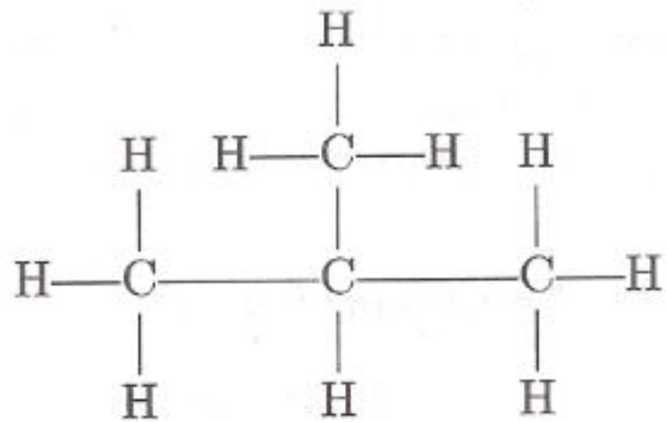
Ethane



Propane

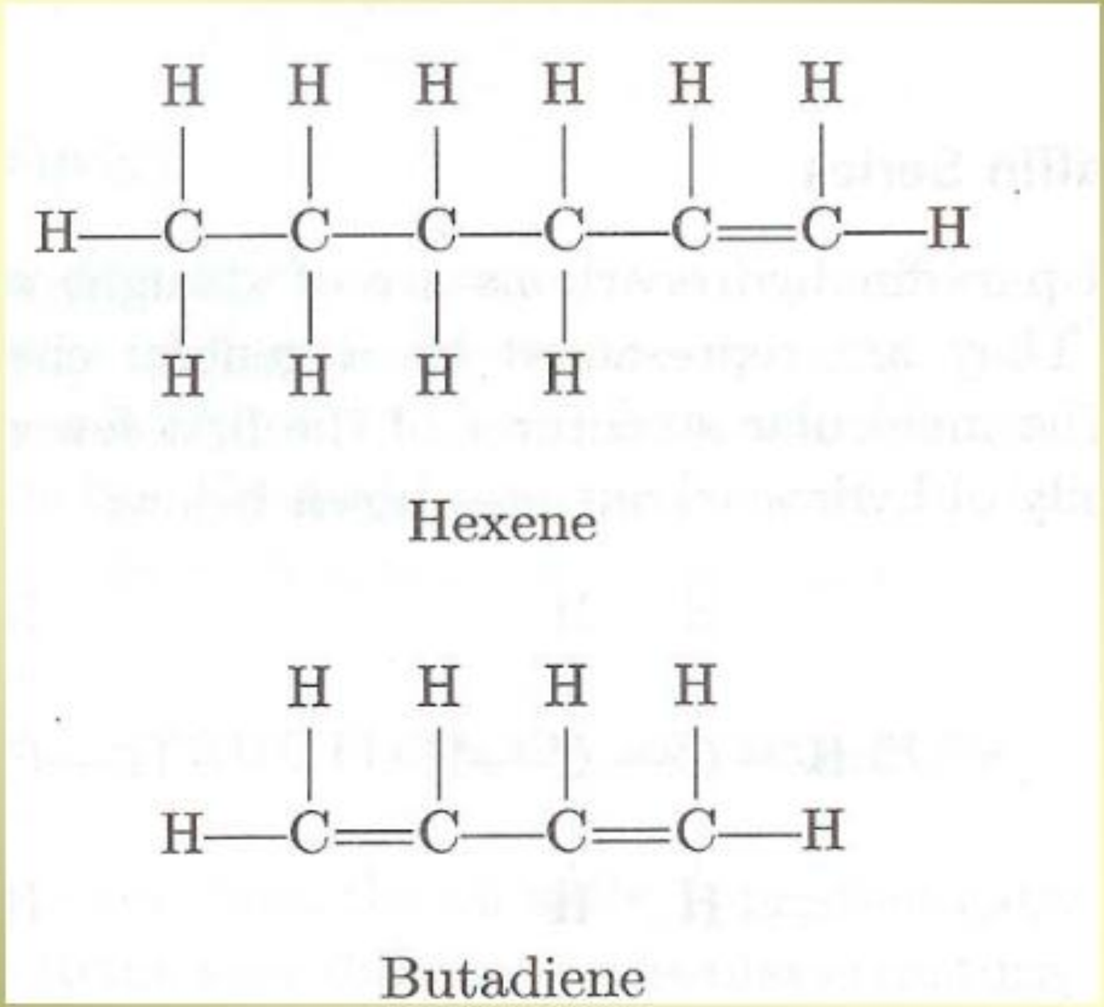


Butane



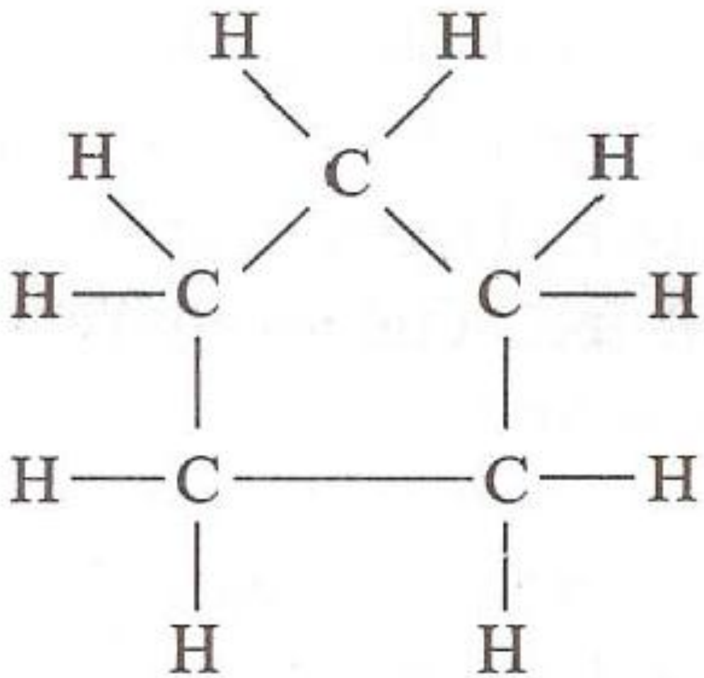
Isobutane

# Olefin series




***Remark:*** ***Unsaturated as they contain one or more double bonds between carbon atoms.***

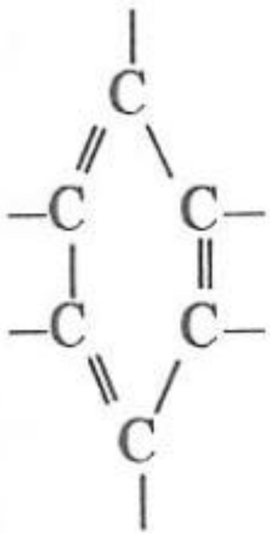
# Naphthene series



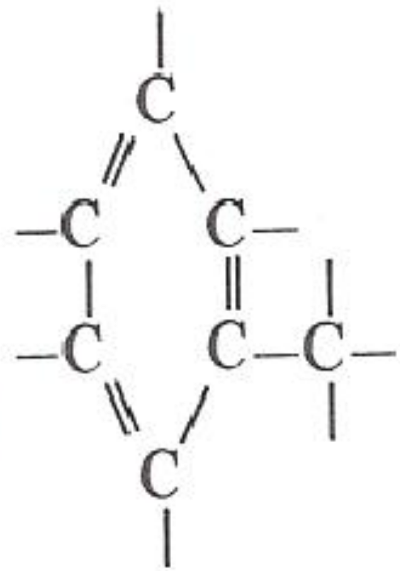
Cyclopentane

**Remark:** ***Have a Ring Structure; Saturated and Stable.***

# Aromatic series



Benzene, $C_6H_6$



Toluene, $C_6H_5CH_3$

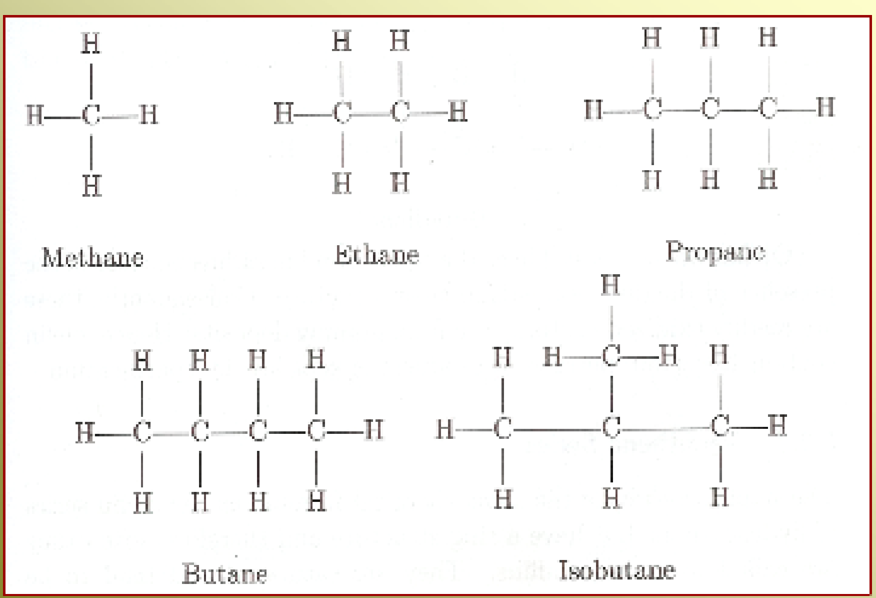
***Remark:* Unsaturated Ring Structure with double carbon-carbon bonds.**

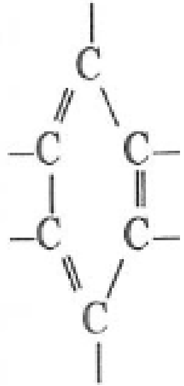
## Aromatics

- Aromatics generally make good gasoline fuel. They have high densities in the liquid state and thus have high energy content per unit volume. Aromatics will dissolve a greater amount of water than some other hydrocarbons. This can create fuel line freezing problems when temperature is lowered and some of the water comes out of solution. Aromatics make poor CI engine fuel.

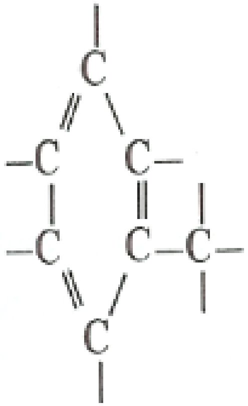
# General Remark

- Antiknock quality improves with increasing no. of carbon atoms and the compactness of molecular structure. Normal paraffins exhibit the poorest antiknock quality when used in SI engine. The aromatics offer the best resistance to knocking in SI engines. For CI engines, normal paraffins are the best fuels.



Benzene, $C_6H_6$



Toluene, $C_6H_5CH_3$

## General Remark

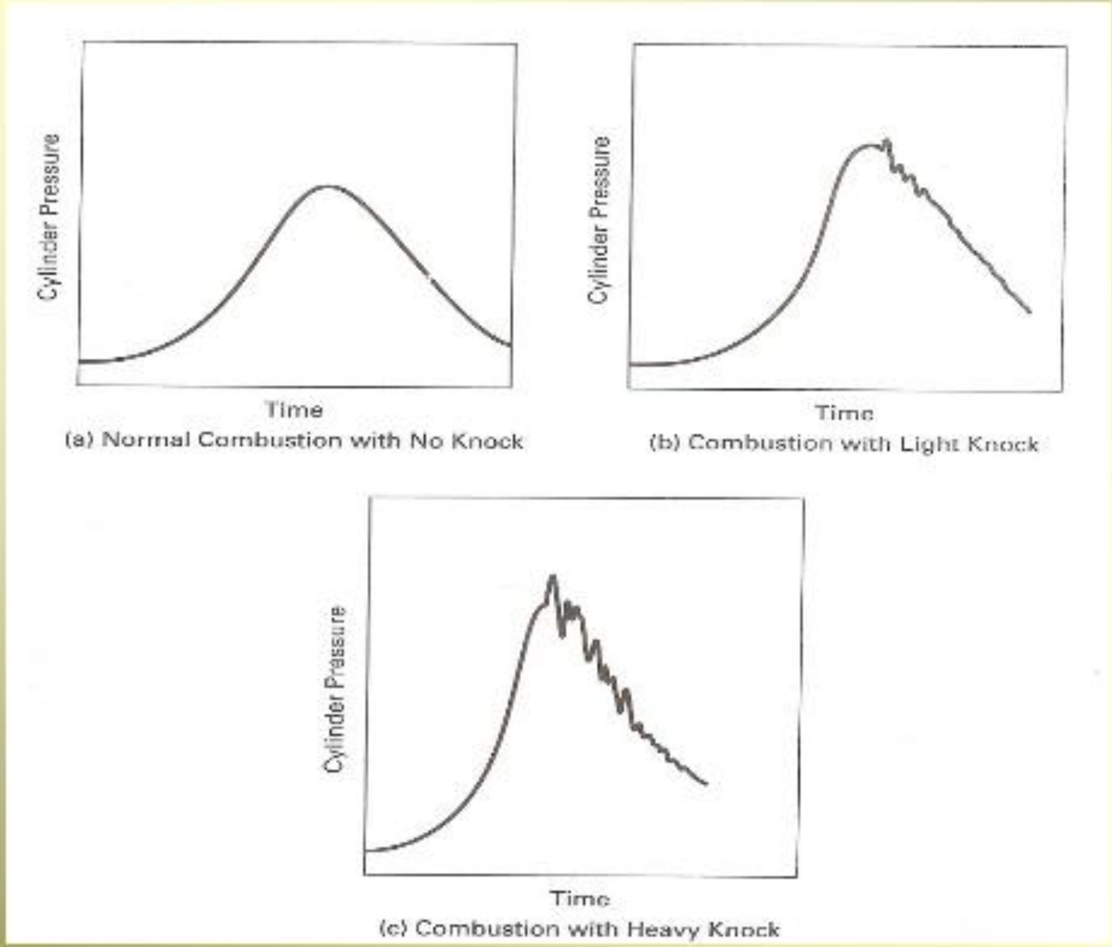
- As the number of atoms in the molecular structure increases, boiling temperature increases. Hence, the fuels with lesser atoms in the molecule are more volatile.

- The heating value increases with increased number of hydrogen atoms in a molecule. Therefore, paraffins have the highest heating value, and the aromatics the least.

## Antiknock Quality

- Abnormal burning/detonation in SI engine causes a very high rate of energy release, temperature and pressure. This adversely affects the thermal efficiency. The fuel characteristics should resist this tendency. This property of fuel is called its antiknock quality.

❑ With no self-ignition, the pressure force on piston follows a smooth curve, resulting in smooth engine operation. **When self-ignition occurs, pressure forces on piston are not smooth and engine knock occurs.**




(a) Normal Combustion with No Knock

(b) Combustion with Light Knock

(c) Combustion with Heavy Knock

# Rating of Fuels

- Fuels are rated for their antiknock qualities.
  - Gasoline : Octane number
  - Diesel : Cetane number

- Resistance to knock depends upon the chemical composition of fuel (or characteristics of hydrocarbon in the fuel).

- Other operating parameters:
  - F-A ratio
  - Ignition timing
  - Engine speed
  - Shape of combustion chamber
  - Compression ratio etc.

# SI Engine Fuels

❖ **Antiknock property is compared with reference to**

- iso-octane ($C_8H_{18}$) ⇒ 100 Octane No.
- heptane ($C_7H_{16}$) ⇒ Zero Octane No.

**Very poor antiknock fuel**

**Very good antiknock fuel**

❖ **Fuel with Octane Number of 70 indicates**

- 70 % octane, and
- 30 % heptane

## Octane Number (ON)

- **Definition:** It indicates the % by volume of iso-octane in a mixture of iso-octane and heptane which exhibit the same characteristics of the fuel in a standard engine under a set of operating conditions.

- Common octane numbers for gasoline fuels used in automobile range from 87 to 95, with higher values for special high performance and racing cars.

# Tests for Rating Octane Number (ON)

- Two most common methods of rating gasoline and other SI engine fuels are the Motor Method and the Research Method. These give the motor octane number (MON) and research octane number (RON).

- Another less common method is the Aviation Method used for aircraft fuel, and this gives an Aviation Octane Number (AON).

# Tests for Rating ON

- The engine used to measure MON and RON was developed in 1930s. It is a single-cylinder, OHV engine that operates on four-stroke Otto cycle with variable compression ratio (3 to 30). Test conditions to measure MON and RON are shown below.

**TABLE 4-3 TEST CONDITIONS FOR OCTANE NUMBER MEASUREMENT**

| | RON | MON |
|---|---|---|
| Engine Speed (RPM): | 600 | 900 |
| Inlet Air Temperature (°C): | 52 (125°F) | 149 (300°F) |
| Coolant Temperature (°C): | 100 (212°F) | 100 |
| Oil Temperature (°C): | 57 (135°F) | 57 |
| Ignition Timing: | 13° bTDC | 19°–26° bTDC |
| Spark Plug Gap (mm): | 0.508 (0.020 in.) | 0.508 |
| Inlet Air Pressure: | atmospheric pressure | |
| Air–Fuel Ratio: | adjusted for maximum knock | |
| Compression Ratio: | adjusted to get standard knock | |

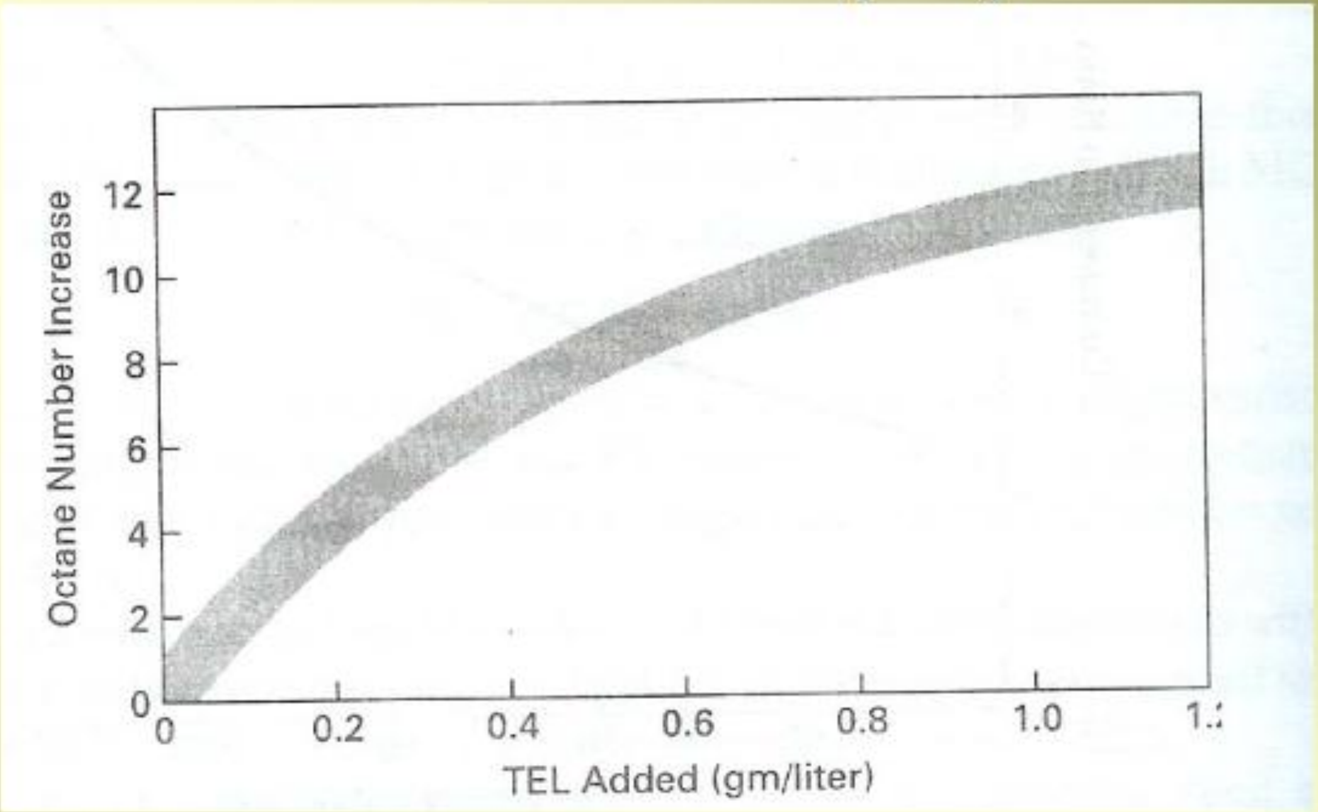
Adapted from [58].

# Tests Procedure

- The test engine is run at specified conditions using the fuel being tested. Compression ratio is varied until a standard level of knock is experienced. The test fuel is then replaced with a mixture of two standard fuels.

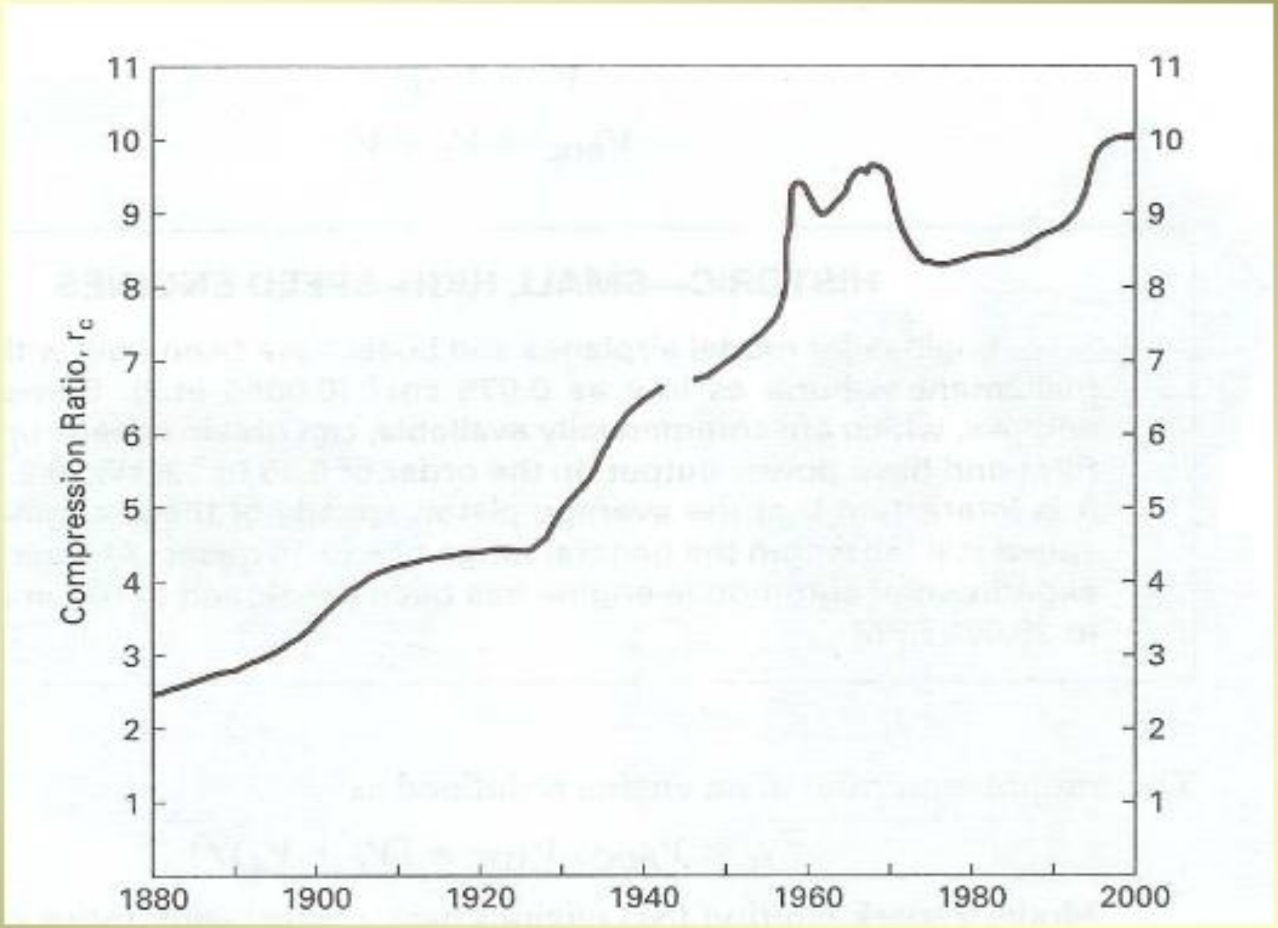
- The intake system of the engine is designed such that the blend of two standard fuels can be varied to any percent *(from all isooctane to all n-heptane)*. The blend of fuels is varied until the same knock characteristics are observed as with the test fuel. The percent of isooctane in the fuel blend is the ON given to the test fuel.

# Octane Number (ON)




- There are a number of gasoline additives that are used to raise the octane number. For many years, the standard additive was tetraethyl lead (TEL). A few millilitres of TEL in several litres of gasoline could raise the ON several points.

# Octane Number (ON)




- The above figures shows how the compression ratios of automobile engines increased after the introduction of TEL in the 1920s.

**Gasoline additives**

| Additives | Type | Function |
| --- | --- | --- |
| Oxidation inhibitors | Aromatic amines and phenols | Inhibit gum formation and oxidation |
| Corrosion inhibitors | Carboxylic acids and carboxylates | Inhibit corrosion of ferrous metals |
| Metal deactivators | Chelating agent | Inhibit gum formation Catalyzed by certain metals |
| Anti-icing additives | Surfactants and glycols | Prevent icing in carburetor and fuel system |
| Detergents | Amines and amine carboxylates | Prevent deposits in carburetor throttle body |
| Deposit control additives | Polybutene amines Polyether amines | Remove and prevent deposits throughout carburetor intake ports and valves |
| Blending agents | Ethanol, methanol, tertiary butyl alcohol, methyl tertiary ether | Extend gasoline supply, increase apparent octane quality with some loss in mileage |
| Antiknock compounds | Lead alkykl, organo-manganese compounds | Increase octane quality |

# CI Engine Fuels

❖ Ignition delay (ID) is the prime factor for auto-ignition/knock.

❖ ID is the time between start of injection and initiation of combustion.

- ❑ Long ID $\Rightarrow$ Rapid pressure rise $\Rightarrow$ Knock
- ❑ Short ID $\Rightarrow$ incomplete mixing/smoke production

❖ Ignition quality : Cetane Number

## Rating of CI Engine Fuel

- **Reference Fuels**
  - Cetane ($C_{16}H_{34}$) ⇒ 100 Cetane No.
  - $\alpha$-methyl naphthalene ($C_{11}H_{10}$) ⇒ Zero Cetane No.
- **Fuel with Cetane Number of 60 indicates**
  - **60 %** $C_{16}H_{34}$
  - **40 %** $C_{11}H_{10}$

**Definition:** It indicates the % by volume of normal cetane in a mixture of Cetane ($C_{16}H_{34}$) and $\alpha$-methyl naphthalene ($C_{11}H_{10}$) which exhibit the same ignition characteristics (ID) as the test fuel when combustion is carried out under specified operating conditions.

# CI Engine Fuels

- Cetane number is a measure of its ability to auto-ignite quickly when the fuel is injected into the combustion chamber.

- Higher the CN, lesser is the tendency to knock. *Further, too high a Cetane number may induce pre-ignition.*

- Diesel usually has a cetane number between 40-60, whereas gasoline has a cetane number of 10-20. This is why it is not suitable as diesel fuel due to its poor auto-ignition quality. *A good diesel engine fuel is a bad gasoline engine fuel.*

## Qualities of CI Engine Fuel

- It should have good antiknock quality. Must have short ignition delay.
- Must be sufficiently volatile in the operating range to ensure proper mixing and complete combustion.
- Should not promote smoke in the exhaust.
- Should not cause corrosion/wear in the engine components.
- Easy handling/availability.

**TABLE 2.13**
**ASTM D975 diesel fuel specifications [by permission of ASTM © 1996]**

| | No. 1D | No. 2D | No. 4D |
|---|---|---|---|
| Flash point (°C, minimum) | 38 | 52 | 55 |
| Cloud point (°C) | Local requirement | Local requirement | Local requirement |
| Water and sediment (vol %, max) | 0.05 | 0.05 | 0.05 |
| Carbon residue 10% Btm (%, max) | 0.15 | 0.35 | — |
| Ash, wt (%, max) | 0.01 | 0.01 | 0.10 |
| Distillation 90% point (°C) | 288 max | 282–338 | — |
| Viscosity at 40°C (cSt) | 1.3–2.4 | 1.9–4.1 | 5.5–24 |
| Sulfur (wt %, max) | 0.05 | 0.05 | 2.0 |
| Copper strip corrosion, max | No. 3 | No. 3 | — |
| Cetane no. (minimum) | 40 | 40 | 30 |

**Fuel no. 1D is used for cold weather applications, and no. 2D is the most common fuel for Diesel vehicles. Number 4D is is used for medium- to low-speed engines used for stationary applications.**

## Diesel Fuel

- In terms of combustion considerations, the major factors are viscosity and cetane number. Although the primary effect of low cetane number is to cause cold starting problems, reduction of cetane number can also increase engine roughness, peak pressure, and NO emissions. Typically, highly turbocharged engines are more tolerant to low cetane number during steady-state operation.

- Diesel fuels can also be improved by addition of fuel-additives.

## Automotive diesel fuel additives

| Additive | Type | Function |
|---|---|---|
| Detergents | Polyglycols, basic nitrogen-containing surfactants | Prevent injector deposits, increase injector life |
| Dispersants | Nitrogen-containing surfactants | Peptize soot and products of fuel oxidant; increase filter life |
| Metal deactivators | Chelating agents | Inhibit gum formation |
| Rust and corrosion inhibitors | Amines, amine carboxylates, and carboxylic acids | Prevent rust and corrosion in pipelines and fuel systems |
| Cetane improvers | Nitrate esters | Increase cetane number |
| Flow improvers | Polymers, wax crystal | Reduce pour point modifiers |
| Antismoke additions or smoke suppressants | Organic barium compounds | Reduce exhaust smoke |
| Oxidation inhibitors | Low–molecular weight amines | Minimize deposits in filters and injectors |
| Biocides | Boron compounds | Inhibit growth of bacteria and microorganisms |

# Summary

**TABLE A-2 PROPERTIES OF FUELS**

| Fuel | | Molecular Weight | Heating Value HHV (kJ/kg) | Heating Value LHV (kJ/kg) | Stoichiometric $(AF)_s$ | Stoichiometric $(FA)_s$ | Octane Number MON | Octane Number RON | Heat of Vaporization (kJ/kg) | Cetane Number |
|---|---|---|---|---|---|---|---|---|---|---|
| gasoline | $C_8H_{15}$ | 111 | 47300 | 43000 | 14.6 | 0.068 | 80–91 | 92–99 | 307 | |
| light diesel | $C_{12.3}H_{22.2}$ | 170 | 44800 | 42500 | 14.5 | 0.069 | | | 270 | 40–55 |
| heavy diesel | $C_{14.6}H_{24.8}$ | 200 | 43800 | 41400 | 14.5 | 0.069 | | | 230 | 35–50 |
| isooctane | $C_8H_{18}$ | 114 | 47810 | 44300 | 15.1 | 0.066 | 100 | 100 | 290 | |
| methanol | $CH_3OH$ | 32 | 22540 | 20050 | 6.5 | 0.155 | 92 | 106 | 1147 | |
| ethanol | $C_2H_5OH$ | 46 | 29710 | 26950 | 9.0 | 0.111 | 89 | 107 | 873 | |
| methane | $CH_4$ | 16 | 55260 | 49770 | 17.2 | 0.058 | 120 | 120 | 509 | |
| propane | $C_3H_8$ | 44 | 50180 | 46190 | 15.7 | 0.064 | 97 | 112 | 426 | |
| nitromethane | $CH_3NO_2$ | 61 | 12000 | 10920 | 1.7 | 0.588 | | | 623 | |
| heptane | $C_7H_{16}$ | 100 | 48070 | 44560 | 15.2 | 0.066 | 0 | 0 | 316 | |
| cetane | $C_{16}H_{34}$ | 226 | 47280 | 43980 | 15.0 | 0.066 | | | 292 | 100 |
| heptamethylnonane | $C_{12}H_{34}$ | 178 | | | 15.9 | 0.063 | | | | 15 |
| α-methylnaphthalene | $C_{11}H_{10}$ | 142 | | | 13.1 | 0.076 | | | | 0 |
| carbon monoxide | CO | 28 | 10100 | 10100 | 2.5 | 0.405 | | | | |
| coal (carbon) | C | 12 | 33800 | 33800 | 11.5 | 0.087 | | | | |
| butene-1 | $C_4H_8$ | 56 | 48210 | 45040 | 14.8 | 0.068 | 80 | 99 | 390 | |
| triptane | $C_7H_{16}$ | 100 | 47950 | 44440 | 15.2 | 0.066 | 101 | 112 | 288 | |
| isodecane | $C_{10}H_{22}$ | 142 | 47590 | 44220 | 15.1 | 0.066 | 92 | 113 | | |
| toluene | $C_7H_8$ | 92 | 42500 | 40600 | 13.5 | 0.074 | 109 | 120 | 412 | |
| hydrogen | $H_2$ | 2 | 141800 | 120000 | 34.5 | 0.029 | | 90 | | |

# References


1. **Borman GL, and Ragland KW**, (1998), *Combustion Engineering*, McGraw Hill.
2. **Crouse WH, and Anglin DL**, (1985), *Automotive Engines*, Tata McGraw Hill.
3. **Eastop TD, and McConkey A,** (1993), *Applied Thermodynamics for Engg. Technologists*, Addison Wisley.
4. **Fergusan CR, and Kirkpatrick AT**, (2001), *Internal Combustion Engines*, John Wiley & Sons.
5. **Ganesan V**, (2003), *Internal Combustion Engines*, Tata McGraw Hill.
6. **Gill PW, Smith JH, and Ziurys EJ**, (1959), *Fundamentals of I. C. Engines*, Oxford and IBH Pub Ltd.
7. **Heisler H,** (1999), *Vehicle and Engine Technology,* Arnold Publishers.
8. **Heywood JB,** (1989), *Internal Combustion Engine Fundamentals*, McGraw Hill.
9. **Heywood JB, and Sher E,** (1999), *The Two-Stroke Cycle Engine*, Taylor & Francis.
10. **Joel R,** (1996), *Basic Engineering Thermodynamics,* Addison-Wesley.
11. **Mathur ML, and Sharma RP,** (1994), *A Course in Internal Combustion Engines,* Dhanpat Rai & Sons, New Delhi.
12. **Pulkrabek WW,** (1997), *Engineering Fundamentals of the I. C. Engine*, Prentice Hall.
13. **Rogers GFC, and Mayhew YR**, (1992), *Engineering Thermodynamics*, Addison Wisley.
14. **Srinivasan S,** (2001), *Automotive Engines*, Tata McGraw Hill.
15. **Stone R,** (1992), *Internal Combustion Engines*, The Macmillan Press Limited, London.
16. **Taylor CF,** (1985), *The Internal-Combustion Engine in Theory and Practice*, Vol.1 & 2, The MIT Press, Cambridge, Massachusetts.