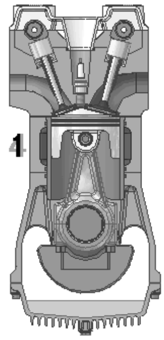
Internal Combustion Engine

- The **internal combustion engine** is an engine in which the combustion of fuel and an oxidizer (typically air) occurs in a confined space called a combustion chamber.
- This exothermic reaction creates gases at high temperature and pressure, which are permitted to expand. Internal combustion engines are defined by the useful work that is performed by the expanding hot gases acting directly to cause the movement of solid parts of the engine

Internal Combustion Engine
Operation

Internal combustion engines have 4 basic steps:

1. **Intake**
   – Combustible mixtures are emplaced in the combustion chamber
2. **Compression**
   – The mixtures are placed under pressure
3. **Combustion/Expansion**
   – The mixture is burnt. The hot mixture is expanded, pressing on and moving parts of the engine and performing useful work.
4. **Exhaust**
   – The cooled combustion products are exhausted
   – Many engines overlap these steps in time, jet engines do all steps simultaneously at different parts of the engines. Some internal combustion engines have extra steps.



Internal Combustion Engine
Ignition

- All internal combustion engines must achieve ignition in their cylinders to create combustion.
- Typically engines use either
  – Spark ignition (SI) method
    - Fuel is ignited through spark generated in spark plugs
  – Compression ignition (CI) system.
    - In a CI engine the fuel is sprayed directly into the cylinder and the vaporised part of the fuel mixes with air and ignites spontaneously.

Internal Combustion Engine
Types

Two basic categories of CI engines:

- **Direct-injection** – have a single open combustion chamber into which fuel is injected directly
- **Indirect-injection** – chamber is divided into two regions and the fuel is injected into the "prechamber" which is connected to the main chamber via a nozzle, or one or more orifices.

Internal Combustion Engine
Knock

Abnormal Combustion in SI Engine

- **Knock** is the term used to describe a pinging noise emitted from a SI engine undergoing abnormal combustion.
- Knock" is the uncontrolled release of energy when combustion initiates somewhere other than the spark plug.
- The noise is generated by shock waves produced in the cylinder when unburned gas autoignites.
- Symptoms of engine "knock" include an audible "knocking" or "pining" sound under acceleration.

Internal Combustion Engine
Knock

- Knock is caused when the temperature in the cylinder reaches the self ignition temperature (SIT) of the end gases.
- The end gases do not readily ignite, rather there is an ignition delay caused by pre-flame reactions.
- Engine knock is more prevalent under conditions that include:
  – Lean air/fuel ratios
  – High compression ratios

Internal Combustion Engine
Knock

Engine parameters that effect occurrence of knock are:

- ***Compression ratio*** – at high compression ratios, even before spark ignition, the fuel-air mixture is compressed to a high pressure and temperature which promotes auto ignition
- ***Engine speed*** – At low engine speeds the flame velocity is slow and thus the burn time is long, this results in more time for auto ignition

Octane Number

- To provide a standard measure of a fuel's ability to resist knock, a scale has been devised by which fuels are assigned an **octane number** ON.
- Octane is a measure of gasoline's resistance to "knock."
- Octane numbers are based on a scale on which isooctane is 100 (minimal knock) and heptane is 0 (bad knock).
- The octane number determines whether or not a fuel will knock in a given engine under given operating conditions.
- The higher the octane number, the higher the resistance to knock.

Octane Rating

- By definition, normal heptane (n-C_7H_{16}) has an octane value of zero and isooctane (C_8H_{18}) has a value of 100.
- Blends of these two hydrocarbons define the knock resistance of intermediate octane numbers: e.g., a blend of 10% n-heptane and 90% isooctane has an octane number of 90.
- A fuel's octane number is determined by measuring what blend of these two hydrocarbons matches the test fuel's knock resistance.

Octane Rating

- An octane rating refers to the measure of the maximum compression ratio at which a particular fuel can be utilized in an engine without some of the fuel /air mixture "knocking" or self igniting.

Octane Rating Measurement

- Procedure developed by the Cooperative Fuels Research Committee (CFR).
- The committee proposed a single cylinder SI engine to measure octane – the CFR engine has an adjustable compression ratio.
- Engine is driven at a constant speed with an electric motor.

Octane Rating Measurement

Testing procedure:

- Run the CFR engine on the test fuel at both research and motor conditions.
- Slowly increase the compression ratio until a standard amount of knock occurs as measured by a magnetostriction knock detector.
- At that compression ratio run the engines on blends of n-heptane and isooctane.
- ON is the % by volume of octane in the blend that produces the stand knock

Octane Ratings

- Motor Octane Number (MON)
  - Run at higher temperatures and RPM's
- Research Octane Number (RON)
  - Determined using a one cycle engine
- Road Octane Number
  - Average of the research octane number and the motor octane number. This is what is displayed on the gas pump.

Octane Ratings

- The most common type of octane rating worldwide is the **Research Octane Number** (**RON**). RON is determined by running the fuel in a test engine with a variable compression ratio under controlled conditions, and comparing the results with those for mixtures of iso-octane and n-heptane.

Octane Ratings

- There is another type of octane rating, called **Motor Octane Number** (**MON**) or the aviation lean octane rating, which is a better measure of how the fuel behaves when under load.
- MON testing uses a similar test engine to that used in RON testing, but with a preheated fuel mixture, a higher engine speed, and variable ignition timing to further stress the fuel's knock resistance.
- Depending on the composition of the fuel, the MON of a modern gasoline will be about 8 to 10 points lower than the RON. Normally fuel specifications require both a minimum RON and a minimum MON.

Octane Rating

- The antiknock index which is displayed at the fuel pump is the average of the research and motor octane numbers:

$$Antiknock\ index = \frac{RON + MON}{2}$$

  - Note the motor octane number is always lower because it uses more severe operating conditions: higher inlet temperature and more spark advance.
  - The automobile manufacturer will specify the minimum fuel ON that will resist knock throughout the engine's operating speed and load range.

Fuel Additives

Chemical additives are used to raise the octane number of gasoline.

- The most effective antiknock agents are lead alkyls;
  (i) Tetraethyl lead (TEL), $(C_2H_5)_4Pb$ was introduced in 1923
  (ii) Tetramethyl lead (TML), $(CH_3)_4Pb$ was introduced in 1960
- In 1959 a manganese antiknock compound known as MMT was introduced to supplement TEL.
- About 1970 low-lead and unleaded gasoline were introduced over toxicological concerns with lead alkyls (TEL contains 64% by weight lead).
- Alcohols such as ethanol and methanol have high knock resistance.
- Since 1970 another alcohol methyl tertiary butyl ether (MTBE) has been added to gasoline to increase octane number. MTBE is formed by reacting methanol and isobutylene

Cetane Number

- **Cetane number** or CN is to diesel fuel what octane rating is to gasoline.
- It is a measure of the fuel's combustion quality.

Compression Ignition

- In a diesel engine, the fuel is ignited by hot air; the air is heated by compression.
- The fuel is injected into this hot air just before the piston reaches top center.
  - Top center" is the moment when the piston has traveled into the cylinder as far as it can go, and compression is at a maximum.
- Ideally, ignition should begin just as the piston reaches top center. If it does not, the entire charge of fuel may have time to become thoroughly mixed with air, and when it does ignite, the pressure rise will be much steeper than it would have been had ignition occurred earlier. So a desirable property of a diesel fuel is that it ignite quickly.

Diesel Fuel

- Because diesels rely on compression ignition (no spark), the fuel must be able to auto-ignite--and generally, the quicker the better.
- A higher cetane number means a shorter ignition delay time and more complete combustion of the fuel charge in the combustion chamber.
- This, of course, translates into a smoother running, better performing engine with more power and fewer harmful emissions.

Cetane Number

- **Cetane Number is a measure of the ignition quality of a diesel fuel.**
- It is often mistaken as a measure of fuel quality. Cetane number is actually a measure of a fuel's ignition delay.
- This is the time period between the start of injection and start of combustion (ignition) of the fuel.
- In a particular diesel engine, higher cetane fuels will have shorter ignition delay periods than lower cetane fuels.

Cetane Number

- Cetane number of a fuel is defined as the percentage by volume of normal cetane in a mixture of normal cetane and alpha-methyl naphthalene which has the same ignition characteristics (ignition delay) as the test fuel when combustion is carried out in a standard engine under specified operating conditions.

Cetane Number

- Cetane rating are an indication of the fuel’s anti-knock resistance for CI engines.
- Fuels with high cetane ratings are created by increasing the proportion of long chain molecules, thereby reducing the ignition delay.
- Fuels with high Octane Rating have low cetane ratings!

Cetane

- **Hexadecane** (also called **cetane**) is an alkane hydrocarbon with the chemical formula $C_{16}H_{34}$.
- Hexadecane consists of a chain of 16 carbon atoms, with three hydrogen atoms bonded to the two end carbon atoms, and two hydrogens bonded to each of the 14 other carbon atoms.
  - It has 10,359 constitutional isomers.
- *Cetane* is often used as a short-hand for cetane number, a measure of the detonation of diesel fuel.

Cetane Number

- Cetane is an alkane molecule that ignites very easily under compression, so it was assigned a cetane number of 100.
- All other hydrocarbons in diesel fuel are indexed to cetane as to how well they ignite under compression.
- The cetane number therefore measures how quickly the fuel starts to burn (auto-ignites) under diesel engine conditions.
- Since there are hundreds of components in diesel fuel, with each having a different cetane quality, the overall cetane number of the diesel is the average cetane quality of all the components.

Ignition Delay

- Ignition delay is defined as the time (or crank angle interval) from when the fuel injection starts to the onset of combustion.
- Both physical and chemical processes must take place before a significant fraction of the fuel chemical energy is released.

Ignition Delay

- ***Physical processes*** are fuel spray atomization, evaporation and mixing of fuel vapour with cylinder air.
- Good atomization requires high fuel pressure, small injector hole diameter, optimum fuel viscosity, high cylinder pressure (large divergence angle).
- Rate of vaporization of the fuel droplets depends on droplet diameter, velocity, fuel volatility, pressure and temperature of the air.

Ignition Delay

- ***Chemical processes*** similar to that described for autoignition phenomenon in premixed fuel-air, only more complex since **heterogeneous reactions** (reactions occurring on the liquid fuel drop surface) also occur.

Effect of Cetane Rating

- If cetane rating is too low, the ignition delay results in hard starting (combustion after piston is moving downward) and characteristic "white smoke."
- High cetane ratings start the combustion process to soon, and some the fuel is not volatized and does not burn.
- "Black smoke" in heavily loaded engines is a symptom of high cetane ratings.
- Minimum cetane rating for CI engines is 40 according to SAE.
- Commercial fuels seldom exceed 50.
- Cetane rating should never exceed 60.

Cetane Number Measurement

- The method used to determine the ignition quality in terms of CN is analogous to that used for determining the antiknock quality via the ON.
- The cetane number scale is defined by blends of two pure hydrocarbon reference fuels.

Cetane Number Measurement

- A specially-designed engine with adjustable compression is used to determine a fuel's cetane number.
- The fuel being tested is injected at 13° before top center.
  - This describes a particular moment in the engine's cycle. "13°" refers to the rotation of the crankshaft.
- The engine's compression ratio is then adjusted until the fuel ignites at top center.

Cetane Number Measurement

- Retaining this compression ratio, the engine is then run on various blends of cetane with 1-methylnapthalene, until a blend is found for which ignition occurs at top center.
- The cetane number is the percentage by volume of cetane in the mixture that has the same performance as the fuel being tested.

Cetane Number Measurement

- In the original procedures **α-methylnaphtalene** ($C_{11}H_{10}$) (CN = 0) was used with **cetane** (n-hexadecane, $C_{16}H_{34}$) (CN = 100).
- This has since been replaced by using a mixture of **cetane** and **isocetane** (heptamethylnonane, HMN) which has a cetane number of 15 and is a more stable compound.

Cetane Number

- Generally, diesel engines run well with a CN from 40 to 55.
- Fuels with higher cetane number which have shorter ignition delays provide more time for the fuel combustion process to be completed. Hence, higher speed diesels operate more effectively with higher cetane number fuels.
- There is no performance or emission advantage when the CN is raised past approximately 55; after this point, the fuel's performance hits a plateau.

Octane versus Cetane Rating

- It is generally observed that there is an inverse relationship of octane and cetane ratings. Wilkes, in 1940, gave the following relationship between the cetane number [CN] and the motor octane number [MON]:

$$CN = 60 - 0.5*MON$$

Cetane Improvers

- These are compounds that readily decompose to give free radicals and thus enhance the rate of chain initiation in diesel combustion.
- They promote fast oxidation of fuels and thus improve their ignition characteristics.
- Chemical compounds such as alkyl nitrates, ether nitrates, dinitrates of polyethylene glycols and certain peroxides are well known cetane improvers.
- In general, however, in view of their low cost and ease of handling, most commercial significance has been attached to different primary alkyl nitrates.