IC ENGINE & GAS TURBINE

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Heat Engine

- A heat engine is a device which transforms the chemical energy of a fuel into thermal energy and uses this energy to produce mechanical work.
- Useful devices since the 17th century, classic example of a heat engine is steam engine

- Classified into two types: External combustion engine and Internal Combustion engine
Products of combustion of air and fuel transfer heat to a second fluid which is the working fluid of the cycle.

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Reciprocating or rotary type</th>
<th>Maximum size in kW</th>
<th>Principal Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Engine</td>
<td>Reciprocating</td>
<td>4000</td>
<td>Locomotives, ships</td>
</tr>
<tr>
<td>Steam Turbine</td>
<td>Rotary</td>
<td>5,00,000</td>
<td>Electric power, large marine</td>
</tr>
<tr>
<td>Stirling or hot air engine</td>
<td>Reciprocating</td>
<td>800</td>
<td>Experimental, power in space, vehicles</td>
</tr>
<tr>
<td>Closed cycle gas turbine</td>
<td>Rotary</td>
<td>80,000</td>
<td>Electric power, marine</td>
</tr>
</tbody>
</table>

In 1690 the first steam piston engine was developed by French physicist Denis Papin for pumping water.

Steam engines are classified into single acting and double acting steam engine, simple and compound steam engine, low speed and high speed steam engine.
It is steam driven rotary engine. Oldest prime mover technology in which potential energy is converted into kinetic energy and then to mechanical energy.

- Wide application in CHP (combined heat and power) plant.
- Thermodynamic cycle is “Rankine cycle”.
- Capacities varies from 50 kWs to hundreds of MWs.

Fig: Steam Turbine in steam power plant
Working of turbine wholly depends upon the dynamic action of the steam
Mechanical work is obtained through expansion Turbine. Expansion takes place through a series of fixed blades (nozzles) and moving blades
In each row fixed blade and moving blades are called stage

Classification of Steam Turbine:

- **Steam Turbine**
  - **Impulse Steam Turbine**
  - **Reaction Steam Turbine**

  - **Simple Steam Turbine** (de Laval)
  - **Compound Steam Turbine**
    - **Velocity compounded** (Curtis)
    - **Pressure compounded** (Rateau)
Steam turbine operation adopt two concepts, which may be used either separately or together. In an impulse turbine the steam is expanded through nozzles so that it reaches a high velocity. The high-velocity, low-pressure jet of steam is then directed against the blades of a spinning wheel, where the steam's kinetic energy is extracted while performing work. Only low-velocity, low-pressure steam leaves the turbine. It’s pressure does not alter as it moves over the blades.

In a reaction turbine the steam expands through a series of stages, each of which has a ring of curved stationary blades and a ring of curved rotating blades. In the rotating section the steam expands partially while providing a reactive force in the tangential direction to turn the turbine wheel. There is gradual fall in the pressure during expansion below the atmospheric pressure.
One of the hot air engines, invented by Robert Stirling (1790-1878)

Aim to replace the steam engine in which frequent explosion caused by unstable high pressure

It is operated by a cyclic compression and expansion of air or other gas (the **working fluid**) at different temperatures

The working gas is generally compressed in the colder portion of the engine and expanded in the hotter portion resulting in a net conversion of heat into **work**

It is closed-cycle regenerative heat engine with a permanently **gaseous** working fluid

practical use largely confined to low-power domestic applications for over a century

Stirling engines can be economical, quieter, safer and less maintenance-free

Fig: Simple Stirling engine
3 major types: alpha, beta and gamma Stirling engine, distinguished by the way they move the air between the hot and cold areas.

**Fig: Alpha Stirling engine**

Two cylinders, expansion cylinder (hot) maintains high temp. and compression cylinder (blue) is cooled. The passage between the two cylinders contains the regenerator.

**Fig: Beta Stirling engine**

Beta-type Stirling engine. There is only one cylinder, hot at one end and cold at the other. A loose-fitting displacer shunts the air between the hot and cold ends of the cylinder. A power piston at the open end of the cylinder drives the flywheel.

**Fig: Gamma Stirling engine**

Simply a Stirling beta engine in which the power piston is not mounted coaxially with the displacer piston but in a separate cylinder.
Closed-cycle gas turbine uses a gas (e.g. air, nitrogen, helium, argon etc.) for the working fluid as part of a closed thermodynamic system. Heat is supplied from an external source.

- No corrosion and accumulation of deposits of carbon or tar on the blade or nozzles of the Turbine. Hence less internal cleaning is required
- Higher turbine efficiency
- Waste heat can be utilized for hot water supply for industrial or domestic purpose
- More complicated and costly
- Coolant is required for cooling
Internal Combustion Engine
### Historical Development:

**1680: Huygens Gunpowder engine**

- **Christian Huygens**
- **Huygens Gun powder engine**

- Internal combustion engine that was to be fueled with gunpowder
- Consists of vertical cylinder, sliding fit type of piston
- Explosion of powder drove the piston on its upward stroke and useful work was produced on the downward stroke of the piston
<table>
<thead>
<tr>
<th>1860: Lenoir Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jean Joseph Etienne Lenoir</td>
</tr>
</tbody>
</table>

- Non-compression combustion gas engine
- Similar to a double acting steam engine in which steam is replaced by the gas formed by the combustion of the charge of air-gas mixture
- Used in modern pulse jet engine
- Low efficiency due to low expansion ratio
<table>
<thead>
<tr>
<th>1866: Free Piston Otto-Langen Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Free Piston Otto-Langen engine" /></td>
</tr>
<tr>
<td>consist of piston without any crankshaft and free to move vertically outwards during the explosion and expansion stroke</td>
</tr>
<tr>
<td>inertia of flywheel raised the piston from bottom position and inducted fresh air-gas charge</td>
</tr>
<tr>
<td>Thermal efficiency is higher than that of the Lenoir engine but its operation is noisy</td>
</tr>
</tbody>
</table>
Beau de Rochas wrote a paper on fundamentals principle of efficient operation of piston combustion engine in **1862**

To achieve maximum expansion ratio, it is required to maintain maximum pressure at the beginning of expansion process.

Theoretical knowledge was adopted by Nikolaus August Otto to built practical four stroke spark ignition engine.
1873: The Brayton engine

- George Bailey Brayton

Brayton Gas engine

- Gas engine version in which gas-air mixture is compressed 4 to 5.5 bar into a receiver and then burnt at constant pressure
- Efficiency is low because of high heat and mechanical friction losses
- Fuel consumption was higher than that of the Otto-Langen atmospheric gas engine
- Brayton cycle or Joule cycle is used in gas turbine engine process
1885: The Atkinson Engine

- Engine which used a short stroke for induction and compression and a longer stroke for expansion and exhaust.
- One cylinder as against of two of Brayton engine and complex linkage mechanism.
- Modern automobile engine e.g. hybrid electric application (Toyota Prius) and non-hybrid vehicles with variable valve timing diagram.
### 1892: The Diesel Engine

<table>
<thead>
<tr>
<th>Rudolf Diesel</th>
<th>First diesel engine</th>
</tr>
</thead>
</table>

- Compression ignition oil engine was developed by German engineer, Rudolf Diesel in 1892.
- First experiment air alone get compressed in compression stroke and coal dust is injected into combustion chamber to initiate combustion.
- Liquid fuel was injected to avoid explosion arise due to coal dust.
- Slow speed diesel engine follows diesel cycle whereas high speed diesel engine adopts combustion process of Otto and diesel engine.
Dugald Clerk

Clerk’s two cycle engine

desirability of having one working stroke in every revolution led to the development of two stroke engine
Separate cylinder was utilised for slight compression of charge
Dr. Felix Wankel

Wankel engine

- Basic design that led to the eventual development of the first successful rotary engine
- Engine has three lobe rotor and the three separate volumes trapped between the rotor and casing
- Major problem in this engine are: Sealing, seal wear and heat transfer
Common application of Internal combustion engine is listed in given table with their service point of view and approximate engine power range in each type of service.

<table>
<thead>
<tr>
<th>Class</th>
<th>Service</th>
<th>Approximate engine power range, kW</th>
<th>Predominant type</th>
<th>D or SI</th>
<th>Cycle</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road vehicles</td>
<td>Motorcycles, scooters</td>
<td>0.75–70</td>
<td>SI</td>
<td>2, 4</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Small passenger cars</td>
<td>15–75</td>
<td>SI</td>
<td>4</td>
<td>A, W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large passenger cars</td>
<td>75–200</td>
<td>SI</td>
<td>4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light commercial</td>
<td>35–150</td>
<td>SI, D</td>
<td>4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heavy (long-distance) commercial</td>
<td>120–400</td>
<td>D</td>
<td>4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Off-road vehicles</td>
<td>Light vehicles (factory, airport, etc.)</td>
<td>1.5–15</td>
<td>SI</td>
<td>2, 4</td>
<td>A, W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Agricultural</td>
<td>3–150</td>
<td>SI, D</td>
<td>2, 4</td>
<td>A, W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Earth moving</td>
<td>40–750</td>
<td>D</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Military</td>
<td>40–2000</td>
<td>D</td>
<td>2, 4</td>
<td>A, W</td>
<td></td>
</tr>
<tr>
<td>Railroad</td>
<td>Rail cars</td>
<td>150–400</td>
<td>D</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Locomotives</td>
<td>400–3000</td>
<td>D</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Marine</td>
<td>Outboard</td>
<td>0.4–75</td>
<td>SI</td>
<td>2</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inboard motorcrafts</td>
<td>4–750</td>
<td>SI, D</td>
<td>4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light naval craft</td>
<td>30–2200</td>
<td>D</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ships</td>
<td>3500–22,000</td>
<td>D</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ships' auxiliaries</td>
<td>75–750</td>
<td>D</td>
<td>4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Airborne vehicles</td>
<td>Airplanes</td>
<td>45–2700</td>
<td>SI</td>
<td>4</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Helicopters</td>
<td>45–1500</td>
<td>SI</td>
<td>4</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Home use</td>
<td>Lawn mowers</td>
<td>0.7–5</td>
<td>SI</td>
<td>2, 4</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Snow blowers</td>
<td>2–5</td>
<td>SI</td>
<td>2, 4</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Light tractors</td>
<td>2–8</td>
<td>SI</td>
<td>4</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Stationary</td>
<td>Building service</td>
<td>7–400</td>
<td>D</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electric power</td>
<td>35–22,000</td>
<td>D</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas pipeline</td>
<td>750–5000</td>
<td>SI</td>
<td>2, 4</td>
<td>W</td>
<td></td>
</tr>
</tbody>
</table>

SI= spark ignition, D=diesel engine, A=Air cooled, W=water cooled
Source: John B. Heywood, “Internal Combustion Engine Fundamentals”
Different components of IC engine

- Cylinder head
- Spark plug
- Inlet valve: to allow air/fuel into the combustion chamber
- Igniting air/fuel mixture
- Combustion chamber
- Piston rings
- Piston
- Gudgeon pin
- Piston cylinder
- Valve stem
- Exhaust valve: to allow burnt fuel out of the combustion chamber
- Clearance volume
- Cylinder
- TDC
- BDC
- Connecting rod
- Crankshaft
- Crank case
- Direction of rotation
Main components of reciprocating IC engines

**Cylinder:**
- main part of the engine inside which piston reciprocates
- ordinary engine is made of cast iron and heavy duty engines are made of steel alloys or aluminum alloys
- In the multi-cylinder engine, the cylinders are cast in one block known as cylinder block.
- Types of block: In-line cylinders, Horizontal opposed cylinders, V-banked cylinders

Application of In-line cylinder arrangement:
1) Commonly used is in-line 4 cylinder or straight 4 (S4) engine
2) S6 engines are used in BMW, Ford, Jeep, Chevrolet, GMC, Toyota, Suzuki and Volvo
3) Aviation use: Stampe SV.4, Tiger moth
4) Motorcycle engines are configured as singles, parallel twins (British motorcycles: 500 CC Sunbeam S7 & S8), triples (Yamaha XS750, BMW K75, Kawasaki KR750, Suzuki TR750 transverse 3s, and Proton/Modenas KR3, Honda NS500 V-3s), fours (Gilera 500 Rondine, Honda CB750) and sixes (1,047 cc Honda CBX, 1,300 cc Kawasaki KZ1300, BMW K1600GT and K1600GTL)
**Application:**
1) Petrol and diesel opposed-piston engines have been used, mostly in large scale applications such as ships, aircraft, military tanks and in factories
2) Diesel Aircraft engine: [Junkers Jumo 205](#)
3) submarines: [Fairbanks Morse 38 8-1/8 diesel engine](#),
4) military boats, locomotives: [Napier Deltic](#) engine, [British Rail Class 55](#) and [British Rail Class 23, Leyland L60, Soviet T-64 tank](#) 5) diesel truck engines: [Commer TS3](#) three-cylinder

**Application:**
1) Vee configuration generally reduces the overall engine length, height and weight compared with an equivalent [inline](#) Configuration
2) V-twin or V-2 engines: used for industrial engines and in several small cars ([Mazda R360](#))
3) other configurations are: V-3,4,5,6,8,10,12, 14,16,18,20,24
### V-engine with various configuration

<table>
<thead>
<tr>
<th>Engine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2 Engine</td>
<td>Widely associated with motorcycles (installed either transversely or longitudinally). V-twin engines have also been used for industrial engines and in several small cars. First V-twin engines were built by Gottlieb Daimler in 1889 and was used as a stationary engine and for boats. Transverse V-twin engines have been used by Harley-Davidson, Ducati and many recent Japanese motorcycles, such as the Suzuki SV650. Longitudinal V-twin engines have been used by the Honda CX series and several Moto Guzzi motorcycles. Mazda R360 rear-engined kei car is Mazda V-twin engine and Mazda B360 front-engine light commercial vehicle used a 577 cc (35.2 cu in) version.</td>
</tr>
<tr>
<td>V3 Engine</td>
<td>V engine with two cylinders in one bank and one cylinder in the other bank, mostly used in two-stroke engines for motorcycles competing in Grand Prix motorcycle racing. Ex: Honda NS5000/NSR500 Grand Prix racing motorcycles, Honda MVX250F, Honda NS400R sports bikes.</td>
</tr>
<tr>
<td>V4 Engine</td>
<td>V4 engines are much less common than inline-four engines, however V4 engines have been used at times in automobiles, motorcycles and other applications. Majority of 2020 MotoGP manufacturers chose the V4 configuration for their bikes e.g. Honda RC213V, Ducati Desmosedici, KTM RC16, Aprilia - 90° V4 for 2020 season.</td>
</tr>
<tr>
<td>V5 Engine</td>
<td>V5 engines are very uncommon, with the only production version being the 1997-2006 Volkswagen Group VR5 engine.</td>
</tr>
<tr>
<td>V6 Engine</td>
<td>First V6 prototype engine was produced in 1906. Luxury cars with V6 engines produce more vibrations than straight-six engines. Sports cars use flat-six engines instead of V6 engines, due to their lower centre of gravity (which improves the handling). V6 engines in open-wheeler racing became more common since the early 2010s such as Formula One World Championship switched to turbocharged V6 engines, FIA Formula 3 Championship (created from the merger of the GP3 Series and the FIA Formula 3 European Championship) began using naturally aspirated V6 engines from 2019.</td>
</tr>
<tr>
<td>V8 Engine</td>
<td>V8 engine was produced by the French company Antoinette in 1904 for use in aircraft. Popularity of V8 engines in cars was greatly increased after introduction of the Ford Flathead V8 in 1932. Can be used in motorcycle for motor racing. Typically used in luxury and racing cars.</td>
</tr>
</tbody>
</table>

Source: https://en.wikipedia.org/wiki/V-twin_engine
Several V10 diesel engines have been produced since 1965, and V10 petrol engines for road cars were first produced in 1991 with the release of the [Dodge Viper](https://en.wikipedia.org/wiki/Dodge_Viper).

### V12 Engine

### V14 Engine

### V16 Engine
Straight 8 banks are balanced. Rarely used in automobiles because V8s or V12s of the same displacement. Few V16s that have been produced were used in high-end luxury and high-performance automobiles due to their smoothness (low vibration). Common applications for V16 engines are railroad locomotives, marine craft, and stationary power generators.

### V18 Engine
Rare configuration not used in automobiles, large V18 diesel engines have seen limited use in mining, electricity generation, rail transport, and marine propulsion. Haul truck (Belaz 75600, Liebherr T 282B, Komatsu 960E-1), Diesel-electric locomotives (MLW M640).

### V20 Engine
Arranged in two cylinder banks of 10, not found in production cars, used in some diesel locomotives, haul trucks, generators and marine applications. [Mercedes-Benz](https://en.wikipedia.org/wiki/Mercedes-Benz) has produced V20 diesel engines used in marine applications. MB 501, MB 511, and the MB 518. [Caterpillar 797F](https://en.wikipedia.org/wiki/Caterpillar_797F) for haul truck and EMD F125 for locomotive produced by Caterpillar Inc.

### V24 Engine
V engine with 24 cylinders, suitable only for very large trucks or locomotives, formed by coupling multiple smaller engines together.

Cylinder head:

- The top end of the cylinder is covered by the cylinder head over which inlet and exhaust valves; spark plug or injectors are mounted.
- Automotive 4-stroke engine head designs are based on different valve and camshaft configuration such as Single overhead camshaft, Double overhead camshaft, overhead valve, side valve, Inter over exhaust, loop flow type, off set cross-flow, in-line cross flow type.
**Piston:**

- Transmit the force exerted by the burning of charge to the connecting rod
- Sustain mechanical and thermal stress
- In case of very high thermal or mechanical stress, the piston is the first component to fail (compared to engine block, valves, cylinder head).
- Made of aluminium alloy which has good heat conducting property and greater strength at higher temperature
- Different types of pistons as per its shape of piston crown such as: flat top, domed, wedge and dished

*Fig: Parts of Piston*
Types of piston as per crown design:

Modern piston types:
Piston rings:

- Housed in the circumferential grooves provided on the outer surface of the piston
- 2 types of rings - compression and oil rings
- Compression ring is upper ring of the piston which provides air tight seal to prevent leakage of the burnt gases into the lower portion. Oil ring is lower ring which provides effective seal to prevent leakage of the oil into the engine cylinder.

Fig: Details of piston ring
**Connecting rod:**

- Converts reciprocating motion of the piston into circular motion of the crank shaft, in the working stroke
- Connects piston and crankshaft by means of pin joints
Crankshaft:

- Converts the reciprocating motion of the piston into the rotary motion with the help of connecting rod
- Supported in main bearings
- Consists of eccentric portion called crank
- Special steel alloys, forging steel, spheroidal graphitic, nickel alloy castings materials are used for the manufacturing of the crankshaft
Crank case:

- It houses cylinder and crankshaft of the IC engine and also serves as sump for the lubricating oil
- Materials used for crank case are like aluminium alloy (higher thermal conductivity), pressed steel sheet
**Valves:**

- Poppet valves control the timing and quantity of gas or vapor flow into an engine.
- Consists of a round head, a stem, and a groove at the top of the valve.
- Proper timing of the opening and closing of the valves is required for smooth operation of an engine.
- Variations include two-stem solid stem valve, hollow head engine valve, and hollow stem engine valve.
- Valve can also be designed with different head shapes such as oval, flat, concave, and recessed head.
Continued...

- **Hollow head engine valve:** extension of the classic sodium-filled hollow valve, with an additional cavity in the valve head. It can sustain the temperature peaks in the valve head and further increase the valve service life.

- **Hollow stem engine valve:** An internally cooled construction has a hollow stem containing a coolant such as metallic sodium or sodium-potassium mixture and is commonly used in extreme duty and high-performance exhaust valves.
Cam Shaft:

- Used to open and close the valves and made of cast iron or forged steel with one cam per valve.
- Camshafts are gear, belt, or chain driven.
- In four stroke cycle engines, camshafts turn at one-half the crankshaft speed.
- Camshaft location: e.g. in in-head valve engines, the camshaft placed at the side along with a push rod and rocker arm. In some cases, camshafts are mounted over the head with cams acting either directly or through a pivoted follower on the valve.

Fig: Camshaft arrangement
Spark Plug:

- In SI engine, spark plug mounted on cylinder head and used to deliver electric current from an ignition system to the combustion chamber for igniting of compressed fuel/air mixture by an electric spark.
- Central electrode tip can be made of copper, nickel-iron, chromium or noble metals.
- Spark plug can go up to maximum 45,000 volts and supply higher current during discharge process, resulting in a hotter and longer-duration spark.
- Temperature of spark channel may reach to 60,000 K.

- Spark plugs in automobiles generally have a gap between 0.6 and 1.8 mm (0.024 and 0.071 in).
Fuel Injector:

- For atomisation and vaporisation of diesel fuel, fuel injectors are used in diesel engine.
- Fuel injector opens and sprays the pressurised fuel into the engine.
- It operates with pulse width and inject proper amount of fuel.

- Injectors are widely used in such diesel equipment as railroad locomotives, trucks, buses, earth movers, ships, and stationary power plants and are sometimes found in aircraft and motor truck spark-ignition engines.
Flywheel:

- Rotating big wheel mounted on the crankshaft which stores the rotational or kinetic energy.
- Its position is between the engine and clutch patch to the starter.
- Serves reservoir which stores energy during power stroke when excess and releases stored energy during idle stroke.
- Controls the speed variations caused by the fluctuation of the engine turning moment during each cycle of operation.
- Flywheel supplies the inertia required to prevent loss of engine speed and possible stoppage of crankshaft rotation between combustion intervals.
Terminology used in IC engine

**Bore (D):** The nominal inner diameter of the working cylinder

**Piston area (A):** The area of circle of diameter equal to the cylinder bore

**Stroke (L):** The nominal distance through which a working piston moves between two successive reversals of its direction of motion

**Bottom dead centre (BDC):** Dead centre when the piston is nearest to the crankshaft

**Top dead centre (TDC):** Dead centre when the position is farthest from the crankshaft
• **Displacement volume or swept volume** \((V_s)\): The nominal volume generated by the working piston when travelling from the one dead centre to next one and given as,
\[
V_s = A \times L = \frac{\pi}{4} D^2 \times L
\]

Cubic centimetres (cc or cm\(^3\)) equivalent to millilitres or Litres
Many automobile manufacturers have adopted Variable displacement technology in large, multi-cylinders engine for improved fuel economy

• **Clearance volume** \((V_c)\): nominal volume of the space on the combustion side of the piston at the top dead centre

• **Cylinder volume** \((V)\): Total volume of the cylinder.
\[
V = V_s + V_c
\]

• **Compression ratio** \((r)\): \(r = \frac{V}{V_c}\)
Classifications of IC Engine

- **Basic engine design**
  - Reciprocating engine (in-line, V, radial, opposed etc.) and rotary engine (Wankel engine: single or two rotor)

- **Working cycle**
  - Otto cycle (Spark ignition engine or petrol engine)
  - Diesel cycle (compression ignition engine or diesel engine)

- **Number of strokes**
  - Four-stroke engine-naturally aspirated (admitting atmospheric air), supercharged (admitting pre-compressed fresh mixture), turbocharged (admitting fresh mixture compressed in a compressor driven by an exhaust turbine), two stroke engine-crankcase scavenged

- **Fuel:**
  - Gasoline, Diesel oil, compressed natural gas, Liquified petroleum gas (LPG), alcohols (methanol, ethanol or butanol, biodiesel, dual fuel or multi-fuel engines)
• Fuel supply and mixture preparation
  carburetted type, Injection type (port fuel injection or IDI, direct injection)

• Method of Ignition
  Spark ignition (conventional petrol engine where mixture is uniform and stratified charge engines where mixtures are non-uniform), Compression engine (conventional diesel engine, as well as gas engine by pilot injection of fuel oil), battery or magneto ignition

• Method of cooling
  Water cooled or air cooled

• Cylinder arrangement
  In-line or straight, V, Radial, Opposed
Contd..

❖ **Combustion chamber design**  
open chamber (many designs as per piston top: e.g., disc, wedge, hemisphere, bowl in piston), divided chamber (small and large auxiliary chambers e.g., swirl chambers, pre-combustion chambers)

❖ **Method of load control**  
Throttling of fuel air flow together so mixture composition is essentially unchanged, control of fuel flow alone, a combination of these

❖ **Valve or port design location**  
Overhead (I head), side valve (L head), in two stroke engine: cross scavenging, loop scavenging, uniflow scavenging

❖ **Application**  
Automotive engines, Marine engines, aircraft engines, industrial engines, military engines, prime movers for electrical generators
Principle of Operation: Four Stroke Engines

- **Suction stroke:** suction valve open, exhaust valve closed, fresh charge admitted
- **Compression stroke:** both valves closed, charge compressed into clearance volume, P & T increases
- **Expansion stroke:** both valves closed, forces piston downwards, power obtained
- **Exhaust stroke:** exhaust valve open, suction valve closed, burned gases expel out
Principle of Operation: Two Stroke Engines

- No piston stroke for suction and exhaust operations
- Suction is accomplished by air compressed in crankcase or by a blower
- Induction of compressed air removes the products of combustion through exhaust ports, therefore no piston strokes required for suction and exhaust operations
- Transfer port is there to supply the fresh charge into combustion chamber
- *loop-scavenged engine, end-to-end scavenged or uniflow scavenged* two stroke engines
## Comparison of Four-stroke and two-stroke engines

<table>
<thead>
<tr>
<th></th>
<th>Four-stroke engines</th>
<th>Two-stroke engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Four stroke of the piston and two revolution of crankshaft</td>
<td>Two stroke of the piston and one revolution of crankshaft</td>
</tr>
<tr>
<td>2.</td>
<td>One power stroke in every two revolution of crankshaft</td>
<td>One power stroke in each revolution of crankshaft</td>
</tr>
<tr>
<td>3.</td>
<td>Heavier flywheel due to non-uniform turning movement</td>
<td>Lighter flywheel due to more uniform turning movement</td>
</tr>
<tr>
<td>4.</td>
<td>Power produce is less</td>
<td>Theoretically power produce is twice than the four-stroke engine for same size</td>
</tr>
<tr>
<td>5.</td>
<td>Heavy and bulky</td>
<td>Light and compact</td>
</tr>
<tr>
<td>6.</td>
<td>Lesser cooling and lubrication requirements</td>
<td>Greater cooling and lubrication requirements</td>
</tr>
<tr>
<td>7.</td>
<td>Lesser rate of wear and tear</td>
<td>Higher rate of wear and tear</td>
</tr>
<tr>
<td>8.</td>
<td>Contains valve and valve mechanism</td>
<td>Contains ports arrangement</td>
</tr>
<tr>
<td>9.</td>
<td>Higher initial cost</td>
<td>Cheaper initial cost</td>
</tr>
<tr>
<td>10.</td>
<td>Volumetric efficiency is more due to greater time of induction</td>
<td>Volumetric efficiency less due to lesser time of induction</td>
</tr>
<tr>
<td>11.</td>
<td>Thermal efficiency is high and also part load efficiency better</td>
<td>Thermal efficiency is low, part load efficiency lesser</td>
</tr>
<tr>
<td>12.</td>
<td>It is used where efficiency is important.</td>
<td>It is used where low cost, compactness and light weight are important.</td>
</tr>
<tr>
<td></td>
<td>Ex-cars, buses, trucks, tractors, industrial engines, aero planes, power generation</td>
<td>Ex-lawn mowers, scooters, motor cycles, mopeds, propulsion ship etc.</td>
</tr>
</tbody>
</table>
# Comparison of SI and CI engine

<table>
<thead>
<tr>
<th>SI engine</th>
<th>CI engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working cycle is Otto cycle.</td>
<td>Working cycle is diesel cycle.</td>
</tr>
<tr>
<td>Petrol or gasoline or high-octane fuel is used.</td>
<td>Diesel or high cetane fuel is used.</td>
</tr>
<tr>
<td>High self-ignition temperature.</td>
<td>Low self-ignition temperature.</td>
</tr>
<tr>
<td>Fuel and air introduced as a gaseous mixture in the suction stroke and get compressed during compression stroke</td>
<td>Fuel is injected directly into the combustion chamber at high pressure at the end of compression stroke.</td>
</tr>
<tr>
<td>Carburettor used to provide the mixture. Throttle controls the quantity of mixture introduced.</td>
<td>Injector and high-pressure pump used to supply of fuel. Quantity of fuel regulated in pump.</td>
</tr>
<tr>
<td>Use of spark plug for ignition system</td>
<td>Self-ignition by the compression of air which increased the temperature required for combustion</td>
</tr>
<tr>
<td>Compression ratio is 6 to 10.5</td>
<td>Compression ratio is 14 to 22</td>
</tr>
<tr>
<td>Higher maximum RPM due to lower weight</td>
<td>Lower maximum RPM</td>
</tr>
<tr>
<td>Maximum efficiency lower due to lower compression ratio</td>
<td>Higher maximum efficiency due to higher compression ratio</td>
</tr>
<tr>
<td>Lighter</td>
<td>Heavier due to higher pressures</td>
</tr>
</tbody>
</table>
Exact moment at which the inlet and outlet valve opens and closes with reference to the position of the piston and crank shown diagrammatically is known as valve timing diagram.

In theoretical cycle, inlet and exhaust valve open and close exactly at the dead centre.

Suction and compression stroke completed in one revolution of the crankshaft. i.e. 360° of crankshaft rotation.

Expansion and exhaust completed in 360° of crankshaft rotation.

Four processes are completed in 720° of crankshaft rotation i.e. two revolution of crankshaft.
### Actual Valve Timing Diagram

**Mechanical Factor:**
- Clearance between cam, tappet, and valve must be slowly taken up to avoid noise and wear.
- “bounce” on its seat

**Dynamic factor:**
In actual valve timing, the opening and closing of the valves taking into consideration due to dynamic effects of gas flow.

**Inlet Valve Timing:**
- SI engine intake valve opens 10° TDC on the exhaust stroke to insure that the valve is fully open
- Inertia of entering fresh charge tends to continue to move into cylinder-ram effect.
- Intake valve should not open for too long after BDC
- Time for opening and closing of intake valve is decided by the speed of the engine.
- At very high speeds, fluid friction hampers the advantage of ram effect.
- For a variable speed engine, the intake valve opening and closing are a compromise between the low and high-speed engine.

**Exhaust Valve Timing:**
- The pressure in cylinder after first portion of expansion stroke is above atmospheric pressure which may increase the work required to expel burnt gas. If exhaust valve is opened some degree before of BDC, then pressure reduces near the end of power stroke.

**Valve overlap**
- Both the intake and exhaust valves are open
- Valve over-lap is 15° in low speed SI engine and 30° in high speed SI engine
- It increase the volumetric efficiency, power output of the engine
Fig: Actual valve timing diagram for low and high-speed SI engine

Fig: Actual valve timing diagram for 4-strokes diesel engine
- Drawn for 2-stroke engine
- No valve arrangement
- 3 ports - inlet, transfer and exhaust

Fig: Port timing diagram for 2-stroke engine
**Otto cycle:**

Process 1-2: reversible adiabatic compression process, isentropic
\( s_1 = s_2 \).

Process 2-3: heat is added at constant volume, state of air changes from point 2 to 3, complete combustion,
combustion efficiency 100%

Process 3-4: Reversible adiabatic expansion process,

hence isentropic, \( s_3 = s_4 \)

Process 4-1: heat is rejected by gases at constant volume

Heat supplied, \( q_s = C_v(T_3 - T_2) \)

Heat rejection, \( q_R = C_v(T_4 - T_1) \)

Compression ratio, \( r_k = \frac{V_1}{V_2} \)

Thermal efficiency, \( \eta_{th} = \frac{q_s - q_R}{q_s} = \frac{C_v(T_3 - T_2) - C_v(T_4 - T_1)}{C_v(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2} \)

Fig: P-V and T-S diagrams of Otto cycle
Contd..

In process 1-2, adiabatic compression process,

\[
\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}
\]

\[=> T_2 = T_1 \cdot (r_k)^{\gamma-1}\]

In adiabatic expansion process, i.e. 3-4,

\[
\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}
\]

\[=> T_3 = T_4 \cdot (r_k)^{\gamma-1}\]

\[
\eta_{th} = 1 - \frac{T_4 - T_1}{T_4 \cdot (r_k)^{\gamma-1} - T_1 \cdot (r_k)^{\gamma-1}} = 1 - \frac{1}{(r_k)^{\gamma-1}}
\]

Work done \((W)\)

Pressure ratio, \(r_p = \frac{p_3}{p_2} = \frac{p_4}{p_1}\)

\[
\frac{p_2}{p_1} = \frac{p_3}{p_4} = \left(\frac{V_1}{V_2}\right)^{\gamma} = (r_k)^{\gamma}
\]
Contd..

\[ W = \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1} \]

\[ = \frac{1}{\gamma - 1} \left[ P_4V_4 \left( \frac{P_3V_3}{P_4V_4} - 1 \right) - P_1V_1 \left( \frac{P_2V_2}{P_1V_1} - 1 \right) \right] \]

\[ = \frac{1}{\gamma - 1} [P_4V_1(r_k^{\gamma-1} - 1) - P_1V_1(r_k^{\gamma-1} - 1)] \]

\[ = \frac{P_1V_1}{\gamma - 1} [r_p(r_k^{\gamma-1} - 1) - (r_k^{\gamma-1} - 1)] \]

\[ = \frac{P_1V_1}{\gamma - 1} [(r_k^{\gamma-1} - 1)(r_p - 1)] \]

Mean effective pressure, \( P_m = \frac{\text{work done}}{\text{swept volume}} = \frac{\text{work done}}{V_1 - V_2} \)

\[ P_m = \frac{P_1V_1}{\gamma - 1} \left[ (r_k^{\gamma-1} - 1)(r_p - 1) \right] = \frac{P_1r_k[(r_k^{\gamma-1} - 1)(r_p - 1)]}{(\gamma - 1)(r_k - 1)} \]
**Diesel cycle:**

Thermodynamic cycle for low speed CI/diesel engine

**Process 1-2:** Reversible adiabatic compression process, work input

**Process 2-3:** Heat addition at constant pressure, air expands from $v_2$ to $v_3$ doing some work. In actual engine heat addition takes place in the form of injection of fuel which self-ignites due to high temperature caused by high compression ratio, and burns at constant pressure. At point 3, called the cut off point, heat or fuel supply is cut off

**Process 3-4:** Reversible adiabatic expansion process, work done on the piston, work out put

**Process 4-1:** at the end of expansion stroke, heat is rejected by gases at constant volume.

- Heat supplied, $Q_1 = C_p(T_3 - T_2)$
- Heat rejection, $Q_2 = C_v(T_4 - T_1)$
- Compression ratio, $\gamma_k = \frac{v_1}{v_2}$
- Cut off ratio, $\gamma_c = \frac{v_3}{v_2}$

**Thermal efficiency,**

$$\eta_{th} = \frac{Q_1 - Q_2}{Q_1} = \frac{c_p(T_3 - T_2) - c_v(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{1}{\gamma} \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

Fig: P-V and T-S diagrams of Diesel cycle
Contd.,

\[ \eta_{th} = 1 - \frac{1}{\gamma} \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{1}{\gamma (r_k)^{\gamma-1}} \left[ \frac{(r_c)^{\gamma} - 1}{r_c - 1} \right] \]

Cut-off ratio should not more than 10% of the stroke as smoking tends to occur in an actual engine

**Work done (W)**

\[
W = P_2(V_3 - V_2) + \frac{P_3V_3 - P_4V_4}{\gamma - 1} - \frac{P_2V_2 - P_1V_1}{\gamma - 1} \\
= P_2(r_cV_2 - V_2) + \frac{P_2r_cV_2 - P_4r_kV_2}{\gamma - 1} - \frac{P_2V_2 - P_1r_kV_2}{\gamma - 1} \\
= P_2V_2 \left[ \frac{(r_c-1)(\gamma-1) + (r_c-r_c^{\gamma}r_k^{1-\gamma})-(1-r_k^{1-\gamma})}{\gamma - 1} \right] \\
= P_1V_1 \cdot r_k^{\gamma-1} \left[ \frac{\gamma(r_c-1)-r_k^{1-\gamma}(r_c^{\gamma}-1)}{\gamma - 1} \right]
\]

Mean effective pressure,

\[
P_m = \frac{P_1V_1 \cdot r_k^{\gamma-1} \left[ \frac{\gamma(r_c-1)-r_k^{1-\gamma}(r_c^{\gamma}-1)}{\gamma - 1} \right]}{V_1 - V_2} = \frac{P_1r_k^{\gamma}[\gamma(r_c-1)-r_k^{1-\gamma}(r_c^{\gamma}-1)]}{(\gamma-1)(r_k-1)}
\]
**Dual cycle or limited pressure cycle**

Thermodynamic cycle for high speed diesel and hot spot ignition engine

Process 1-2: Reversible adiabatic compression process, work input
Process 2-3: Heat addition at constant volume tends to increase thermal efficiency
Process 3-4: Heat addition at constant pressure limits the maximum pressure
Process 4-5: Reversible adiabatic expansion process, work done on the piston, work output
Process 5-1: at the end of expansion stroke, heat is rejected by gases at constant volume.

Total heat supplied, \( Q_1 = C_v(T_3-T_2) + C_p(T_4-T_3) \)
Heat rejection, \( Q_2 = C_v(T_5-T_1) \)
Compression ratio, \( r_k = \frac{V_1}{V_2} \)
Cut off ratio, \( r_c = \frac{V_4}{V_3} \)
Pressure ratio, \( r_p = \frac{P_3}{P_2} \)

Fig: P-V and T-S diagrams of Dual cycle
\[ \eta_{th} = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} = 1 - \frac{1}{(r_k)^{\gamma - 1}} \left[ \frac{r_p(r_c)^{\gamma - 1}}{(r_p - 1) + \gamma r_p(r_c - 1)} \right] \]

Work done (W)

\[ W = P_3(V_4 - V_3) + \frac{P_4 V_4 - P_5 V_5}{\gamma - 1} - \frac{P_2 V_2 - P_1 V_1}{\gamma - 1} \]

\[ = P_3 V_3 (r_c - 1) + \frac{(P_4 r_c V_3 - P_5 r_k V_3) - (P_2 V_3 - P_1 r_k V_3)}{\gamma - 1} \]

\[ = \frac{P_1 V_1 \cdot r_k^{\gamma - 1} \left[ \gamma r_p(r_c - 1) + (r_p - 1) \cdot r_k^{\gamma - 1} (r_p r_c r_c^{\gamma - 1}) \right]}{\gamma - 1} \]

Mean effective pressure,

\[ P_m = \frac{P_1 V_1 \cdot r_k^{\gamma - 1} \left[ \gamma r_p(r_c - 1) + (r_p - 1) \cdot r_k^{\gamma - 1} (r_p r_c r_c^{\gamma - 1}) \right]}{\gamma - 1} \]

\[ = \frac{P_1 r_k^{\gamma} \left[ r_p(r_c - 1) + (r_p - 1) \cdot r_k^{1-\gamma} (r_p r_c r_c^{\gamma - 1}) \right]}{(\gamma - 1)(r_k - 1)} \]
Comparison of Otto, Diesel and Dual cycle:

(a) For same compression ratio and same heat input

\[ (\eta_{th})_{Otto} > (\eta_{th})_{Dual} > (\eta_{th})_{Diesel} \]

(a) For constant maximum pressure and same heat input

\[ (\eta_{th})_{Diesel} > (\eta_{th})_{Dual} > (\eta_{th})_{Otto} \]

(a) For same maximum pressure and temperature

\[ (\eta_{th})_{Diesel} > (\eta_{th})_{Dual} > (\eta_{th})_{Otto} \]

(a) For same maximum pressure and output

\[ (\eta_{th})_{Diesel} > (\eta_{th})_{Otto} \]
Text Books:

Reference Books:

Website collection:
https://www.mpoweruk.com/heat_engines.htm
http://www.fem.unicamp.br/~em313/paginas/consulte/steame.htm
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