CHAPTER 1

Internal Combustion Engine

1.1 Historical Overview of IC Engine Development

The modern reciprocating internal combustion engines have their origin in the Otto and Diesel Engines invented in the later part of 19th century. The main engine components comprising of piston, cylinder, crank-slider crankshaft, connecting road, valves and valve train, intake and exhaust system remain functionally overall similar since those in the early engines although great advancements in their design and materials have taken place during the last 100 years or so. An historical overview of IC engine development with important milestones since their first production models were built, is presented in Table 1.1.

Table 1.1 Historical Overview and Milestones in IC Engine Development

Year	Milestone
1860-1867	J. E. E. Lenoir and Nikolaus Otto developed atmospheric engine wherein combustion of fuel-air charge during first half of outward stroke of a free piston accelerating the piston which was connected to a rack assembly. The free piston would produce work during second half of the stroke creating vacuum in the cylinder and the atmospheric pressure then would push back the piston.
1876	Nikolaus Otto developed 4-stroke SI engine where in the fuel-air charge was compressed before being ignited.

Table 1.1 ***Contd…***

Year	Milestone
1878	Dugald Clerk developed the first 2-stroke engine.
1882	Atkinson develops an engine having lower expansion stroke than the compression stroke for improvement in engine thermal efficiency at cost of specific engine power. The Atkinson cycle is finding application in the modern hybrid electric vehicles (HEV).
1892	Rudolf Diesel takes patent on engine having combustion by direct injection of fuel in the cylinder air heating solely by compression, the process now known as compression ignition (CI).
1896	Henry Ford develops first automobile powered by the IC engine.
1897	Rudolph Diesel developed CI engine prototype, also called as the Diesel engine.
1923	Antiknock additive tetra ethyl lead discovered by the General Motors became commercially available which provided boost to development of high compression ratio SI engines.
1957	Felix Wankel developed rotary internal combustion engine.
1981	Multipoint port fuel injection introduced on production gasoline cars.
1988	Variable valve timing and lift control introduced on gasoline cars.
1989-1990	Electronic fuel injection on heavy duty diesel introduced.
1990	Carburettor was replaced by port fuel injection on all US production cars.
1994	Direct injection stratified charge (DISC) engine powered cars came in production by Mitsubishi and Toyota.

The internal combustion engine is a heat engine that converts chemical energy in a fuel into mechanical energy, usually made available on a rotating output shaft.

Chemical energy of the fuel is first converted to thermal energy by means of combustion or oxidation with air inside the engine. This thermal energy raises the temperature and pressure of the gases within the engine and the high-pressure gas then expands against the mechanical mechanisms of the engine. This expansion is converted by the mechanical linkages of the engine to a rotating crankshaft, which is the output of the engine. Schematic view of IC Engine is shown in Fig. 1.1.

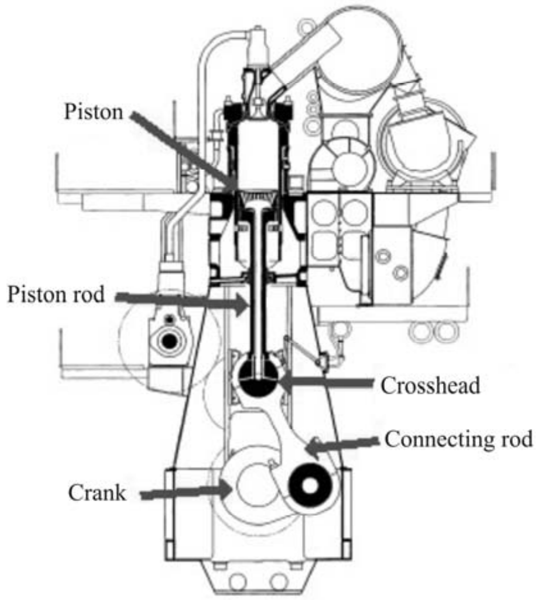

Fig. 1.1 Schematic View of IC Engine

The crankshaft, in turn, is connected to a transmission and/or power train to transmit the rotating mechanical energy to the desired final use. For engines this will often be the propulsion of a vehicle (i.e., automobile, truck, locomotive, marine vessel, or airplane). Other applications include stationary engines to drive generators or pumps, and portable engines for things like chain saws and lawn mowers.

Most internal combustion engines are reciprocating engines having pistons that reciprocate back and forth in cylinders internally within the engine.

1.2 Classification of Internal Combustion Engine

Internal combustion engines can be classified in a number of different ways:

(i) Types of Ignition

(a) ***Spark Ignition (SI):*** An SI engine starts the combustion process in each cycle by use of a spark plug. The spark plug gives a high-voltage electrical discharge between two electrodes which ignites the air-fuel mixture in the combustion chamber surrounding the plug. In early engine development, before the invention of the electric spark plug, many forms of torch holes were used to initiate combustion from an external flame.

(b) ***Compression Ignition (CI):*** The combustion process in a CI engine starts when the air-fuel mixture self-ignites due to high temperature in the combustion chamber caused by high compression.

(ii) Engine Cycle

(a) ***Four-Stroke Cycle:*** A four-stroke cycle experiences four piston movements over two engine revolutions for each cycle.

(b) ***Two-Stroke Cycle:*** A two-stroke cycle has two piston movements over one engine revolution for each cycle.

Three-stroke cycles and six-stroke cycles were also tried in early engine development.

(iii) Valve Location

(a) Valves in head (overhead valve), also called I Head engine.

(b) Valves in block (flat head), also called L Head engine. Some historic engines with valves in block had the intake valve on one side of the cylinder and the exhaust valve on the other side. These were called T Head engines.

(c) One valve in head (usually intake) and one in block, also called F Head engine; this is much less common.

(iv) Basic Design

(a) ***Reciprocating:*** Engine has one or more cylinders in which pistons reciprocate back and forth. The combustion chamber is located in the closed end of each cylinder. Power is delivered to a rotating output crankshaft by mechanical linkage with the pistons.

(b) ***Rotary:*** Engine is made of a block (stator) built around a large non-concentric rotor and crankshaft. The combustion chambers are built into the non-rotating block.

(v) Position and Number of Cylinders of Reciprocating Engines

(a) ***Single Cylinder:*** Engine has one cylinder and piston connected to the crankshaft.

(b) ***In-Line:*** Cylinders are positioned in a straight line, one behind the other along the length of the crankshaft. They can consist of 2 to 11 cylinders or possibly more. In-line four-cylinder engines are very common for automobile and other applications. In-line six and eight cylinders are historically common automobile engines. In-line engines are sometimes called straight (e.g., straight six or straight eight).

(c) ***V Engine:*** Two banks of cylinders at an angle with each other along a single crankshaft. The angle between the banks of cylinders can be anywhere from 15° to 120°, with 60°-90° being common. V engines have even numbers of cylinders from 2 to 20 or more. V6s and V8s are common automobile engines, with V12s and V16s (historic) found in some luxury and high-performance vehicles.

(d) ***Opposed Cylinder Engine:*** Two banks of cylinders opposite each other on a single crankshaft (a V engine with a 180°V). These are common on small aircraft and some automobiles with an even number of cylinders from two to eight or more. These engines are often called flat engines (e.g., flat four).

(e) ***W Engine:*** Same as a V engine except with three banks of cylinders on the same crankshaft. Not common, but some have been developed for racing automobiles, both modern and historic. Usually 12 cylinders with about a 60° angle between each bank.

(f) ***Opposed Piston Engine:*** Two pistons in each cylinder with the combustion chamber in the center between the pistons. A single-combustion process causes two power strokes at the same time, with each piston being pushed away from the center and delivering power to a separate crankshaft at each end of the cylinder. Engine output is either on two rotating crankshafts or on one crankshaft incorporating complex mechanical linkage.

(g) ***Radial Engine:*** Engine with pistons positioned in a circular plane around the central crankshaft. The connecting rods of the pistons are connected to a master rod which, in turn, is connected to the crankshaft. A bank of cylinders on a radial engine always has an odd number of cylinders ranging from 3 to 13 or more. Operating on a four-stroke cycle, every other cylinder fires and has a power stroke as the crankshaft rotates, giving a smooth operation. Many medium and large-size propeller-driven aircraft use radial engines. For large aircraft, two or more banks of cylinders are mounted together, one behind the other on a single crankshaft, making one powerful, smooth engine. Very large ship engines exist with up to 54 cylinders, six banks of 9 cylinders each.

(vi) Air Intake Process

(a) ***Naturally Aspirated:*** No intake air pressure boost system exists.

(b) ***Supercharged:*** Intake air pressure increased with the compressor driven off of the engine crankshaft.

(c) ***Turbocharged:*** Intake air pressure increased with the turbine-compressor driven by the engine exhaust gases.

(d) ***Crankcase Compressed:*** Two-stroke cycle engine uses the crankcase as the intake air compressor. Limited development work has also been done on design and construction of four-stroke cycle engines with crankcase compression.

(vii) Method of Fuel Input for SI Engines

(a) Carbureted.

(b) *Multipoint Port Fuel Injection:* One or more injectors at each cylinder intake.

(c) *Throttle Body Fuel Injection:* Injectors upstream in intake manifold.

(viii) Fuel Used

(a) Gasoline.

(b) Diesel Oil or Fuel Oil.

(c) Gas, Natural Gas, Methane.

(d) LPG.

(e) Alcohol-Ethyl, Methyl.

(f) *Dual Fuel:* There are a number of engines that use a combination of two or more fuels. Some, usually large, CI engines use a combination of methane and diesel fuel. These are attractive in third world developing countries because of the high cost of diesel fuel. The engine which runs on Combined gasoline-alcohol fuels are called dual fuel engines.

(g) *Gasohol:* Common fuel is consisting of 90% gasoline and 10% alcohol.

(ix) Application

(a) Automobile, Truck, Bus.

(b) Locomotive.

(c) Stationary.

(d) Marine.

(e) Aircraft.

(f) Small Portable, Chain Saw, Model Airplane.

(x) Type of Cooling

(a) Air Cooled.

(b) Liquid Cooled, Water Cooled.

1.3 Nomenclature

The following terms are commonly used in IC engine technology literature and also shown in Fig. 1.2.

Spark Ignition (SI): An engine in which the combustion process in each cycle is started by use of a spark plug.

Compression Ignition (CI): An engine in which the combustion process starts when the air-fuel mixture self-ignites due to high temperature in the combustion chamber caused by high compression. CI engines are often called Diesel engines.

Top-Dead-Center (TDC): Position of the piston when it stops at the furthest point away from the crankshaft. Top, because this position is at the top of most engines (not always), and dead because the piston stops at this point. Because in some engines top-dead-center is not at the top of the engine (e.g., horizontally opposed engines, radial engines, etc.,) some sources call this position Head-End-Dead-Center (HEDC).

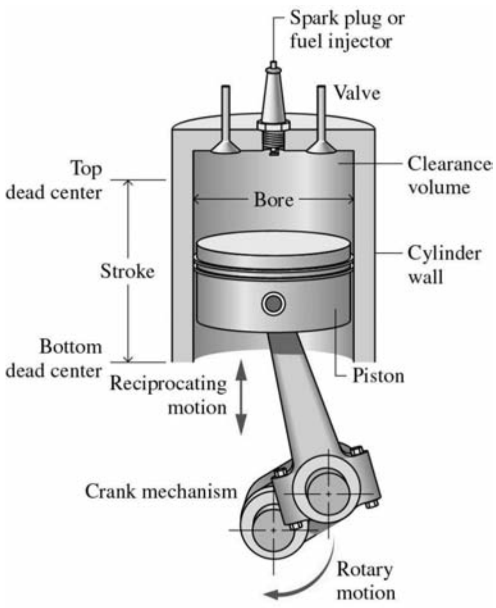

Fig. 1.2 Term Relating in IC Engine

Bottom-Dead-Center (BDC): Position of the piston when it stops at the point closest to the crankshaft. Some sources call this Crank-End-Dead-Center (CEDC) because it is not always at the bottom of the engine.

Bore (D): Diameter of the cylinder or diameter of the piston face, which is the same minus a very small clearance.

Stroke (L): Movement distance of the piston from one extreme position to the other i.e., TDC to BDC or BDC to TDC. It is equal to twice the radius of crank circle.

Clearance Volume: Minimum volume in the combustion chamber with piston at TDC.

Displacement or Displacement Volume: Volume displaced by the piston as it travels through one stroke. Displacement can be given for one cylinder or for the entire engine (one cylinder times number of cylinders). Some literature calls this *Swept Volume*.

$$V_s = \frac{\pi D^2 L}{4}$$

Compression Ratio (CR): It is the ratio of total volume to clearance volume.

1.4 Parts of Internal Combustion Engine

The following are the major components found in most reciprocating internal combustion engines (Fig. 1.3).

(i) ***Block:*** Body of engine containing the cylinders, made of cast iron or aluminum. The block of water-cooled engines includes a water jacket cast around the cylinders. On air-cooled engines, the exterior surface of the block has cooling fins.

(ii) ***Camshaft:*** Rotating shaft used to push open valves at the proper time in the engine cycle, either directly or through mechanical or hydraulic linkage (push rods, rocker arms, tappets). Most modern automobile engines have one or more camshafts mounted in the engine head (overhead cam). Camshafts are generally made of forged steel or cast iron and are driven off the crankshaft by means of a belt or chain (timing chain).

(iii) ***Carburetor:*** Venturi flow device which meters the proper amount of fuel into the air flow by means of a pressure differential.

(iv) ***Catalytic Converter:*** Chamber mounted in exhaust flow containing catalytic material that promotes reduction of emissions by chemical reaction.

(v) ***Combustion Chamber:*** The end of the cylinder between the head and the piston face where combustion occurs. The size of the combustion chamber continuously changes from a minimum volume when the piston is at TDC to a maximum when the piston is at BDC.

(vi) ***Connecting Rod:*** Rod connecting the piston with the rotating crankshaft, usually made of steel or alloy forging in most engines but may be aluminum in some small engines.

(vii) ***Connecting Rod Bearing:*** Bearing where connecting rod fastens to crankshaft.

(viii) **Cooling Fins:** Metal fins on the outside surfaces of cylinders and head of an air-cooled engine. These extended surfaces cool the cylinders by conduction and convection.

(ix) **Crankcase:** Part of the engine block surrounding the rotating crankshaft. In many engines, the oil pan makes up part of the crankcase housing.

(x) **Crankshaft:** Rotating shaft through which engine work output is supplied to external systems. The crankshaft is connected to the engine block with the main bearings. It is rotated by the reciprocating pistons through connecting rods connected to the crankshaft. Most crankshafts are made of forged steel, while some are made of cast iron.

(xi) **Cylinders:** The circular cylinders in the engine block in which the pistons reciprocate back and forth. The walls of the cylinder have highly polished hard surfaces. Cylinders may be machined directly in the engine block, or a hard metal (drawn steel) sleeve may be pressed into the softer metal block.

(xii) **Exhaust Manifold:** Piping system which carries exhaust gases away from the engine cylinders, usually made of cast iron.

(xiii) **Exhaust System:** Flow system for removing exhaust gases from the cylinders, treating them, and exhausting them to the surroundings. It consists of exhaust manifold which carries the exhaust gases away from the engine, a thermal or catalytic converter to reduce emissions, a muffler to reduce engine noise.

(xiv) **Flywheel:** Rotating mass with a large moment of inertia connected to the crank-shaft of the engine. The purpose of the flywheel is to store energy and furnish a large angular momentum that keeps the engine rotating between power strokes and smoothes out engine operation.

(xv) **Fuel Injector:** A pressurized nozzle that sprays fuel into the incoming air on SI engines or into the cylinder on CI engines. On SI engines, fuel injectors are located at the intake valve ports on multipoint port injector systems and upstream at the intake manifold inlet on throttle body injector systems. In a few SI engines, injectors spray directly into the combustion chamber.

(xvi) **Fuel Pump:** Electrically or mechanically driven pump to supply fuel from the fuel tank (reservoir) to the engine. Many modern automobiles have an electric fuel pump mounted submerged in the fuel tank. Some small engines and early automobiles had no fuel pump, relying on gravity feed.

(xvii) **Head:** The piece which closes the end of the cylinders, usually containing part of the clearance volume of the combustion chamber. The head is usually made of cast iron or aluminum, and bolts to the engine block. In some engines, the head is one piece with the block. The head contains the spark plugs in SI engines and the fuel injectors in CI engines. Most modern engines have the valves in the head.

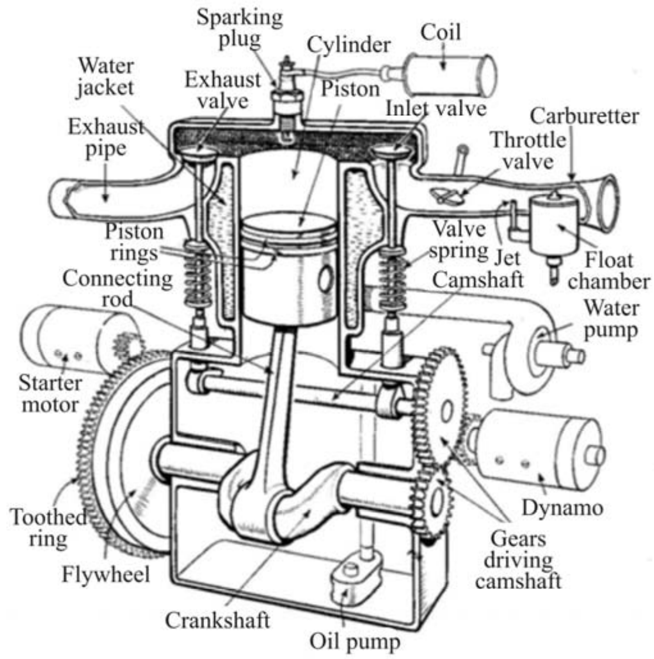

Fig. 1.3 Construction of Four-Stroke Cycle SI Engine

(xviii) **Head Gasket:** Gasket which serves as a sealant between the engine block and head where they bolt together. They are usually made in sandwich construction of metal and composite materials.

(xix) **Intake Manifold:** Piping system which delivers incoming air to the cylinders usually made of cast metal, plastic, or composite material. In most SI engines, fuel is added to the air in the intake manifold system either by fuel injectors or with a carburetor.

(xx) **Oil Pump:** Pump used to distribute oil from the oil sump to required lubrication points. The oil pump can be electrically driven, but is most commonly mechanically driven by the engine. Some small engines do not have an oil pump and are lubricated by splash distribution.

(xxi) **Oil Dump:** Reservoir for the oil system of the engine, commonly part of the crankcase.

(xxii) **Piston:** The cylindrical-shaped mass that reciprocates back and forth in the cylinder, transmitting the pressure forces in the combustion chamber to the rotating crankshaft. The top of the piston is called the crown and the sides are called the skirt. The face on the crown makes up one wall of the combustion chamber and may be a flat or highly contoured surface. Pistons are made of cast iron, steel, or aluminum. Iron and steel pistons can have sharper corners because of their higher strength. Aluminum pistons are lighter and have less mass inertia. Sometimes synthetic or composite materials are used for the body of the piston. Some pistons have a ceramic coating on the face.

(xxiii) **Piston Rings:** Metal rings that fit into circumferential grooves around the piston and form a sliding surface against the cylinder walls. Near the top of the piston are usually two or more compression rings made of highly polished hard chrome steel. The purpose of these is to form a seal between the piston and cylinder walls and to restrict the high-pressure gases in the combustion chamber from leaking past the piston into the crankcase. Below the compression rings on the piston is at least one oil ring, which assists in lubricating the cylinder walls and scrapes away excess oil to reduce oil consumption.

(xxiv) **Push Rods:** Mechanical linkage between the camshaft and valves on overhead valve engines with the camshaft in the crankcase.

(xxv) **Spark Plug:** Electrical device used to initiate combustion in an SI engine by creating a high-voltage discharge across an electrode gap. Spark plugs are usually made of metal surrounded with ceramic insulation.

(xxvi) **Super Charger:** Mechanical compressor powered off of the crankshaft, used to compress incoming air of the engine.

(xxvii) **Throttle:** Butterfly valve mounted at the upstream end of the intake system, used to control the amount of air flow into an SI engine. Some small engines and stationary constant-speed engines have no throttle.

(xxviii) **Turbo Charger:** Turbine-compressor used to compress incoming air into the engine.

The turbine is powered by the exhaust flow of the engine and thus takes very little useful work from the engine.

(xxix) **Valves:** Used to allow flow into and out of the cylinder at the proper time in the cycle. Most engines use poppet valves, which are spring loaded closed and pushed open by camshaft action. Valves are mostly made of forged steel. Many two-stroke cycle engines have ports (slots) in the side of the cylinder walls instead of mechanical valves.

(xxx) **Wrist Pin:** Pin fastening the connecting rod to the piston (also called the piston pin).

1.5 Spark Ignition Engine (Petrol Engine)

1.5.1 Working of 2-Stroke SI Engine

(i) ***Combustion:*** With the piston at TDC combustion occurs very quickly, raising the temperature and pressure to peak values, almost at constant volume (Fig. 1.4(e)).

(ii) ***First Stroke (Expansion Stroke or Power Stroke):*** Very high pressure created by the combustion process forces the piston down in the power stroke. The expanding volume of the combustion chamber causes pressure and temperature to decrease as the piston travels towards BDC (Fig. 1.4 (a)).

(iii) ***Exhaust Blowdown:*** At about BDC, the exhaust valve opens and blowdown occurs. The exhaust valve may be a poppet valve in the cylinder head, or it may be a slot in the side of the cylinder which is uncovered as the piston approaches BDC. After blowdown the cylinder remains filled with exhaust gas at lower pressure (Fig. 1.4(b)).

(iv) ***Intake and Scavenging:*** When blowdown is nearly complete, at about BDC, the intake slot on the side of the cylinder is uncovered and intake air-fuel enters under pressure. Fuel is added to the air with either a carburetor or fuel injector. This incoming mixture pushes much of the remaining exhaust gases out the open exhaust valve and fills the cylinder with a combustible air-fuel mixture, a process called scavenging. The piston passes BDC and very quickly covers the intake port and then the exhaust port (or the exhaust valve closes). The higher pressure at which the air enters the cylinder is established in one of two ways. Large two-stroke cycle engines generally have a supercharger, while small engines will intake the air through the crankcase. On these engines the crankcase is designed to serve as a compressor in addition to serving its normal function (Fig. 1.4(c)).

(v) ***Second Stroke (Compression Stroke):*** With all valves (or ports) closed, the piston travels towards TDC and compresses the air-fuel mixture to a higher pressure and temperature. Near the end of the compression stroke, the spark plug is fired; by the time the piston gets to IDC, combustion occurs and the next engine cycle begins (Fig. 1.4(d)).

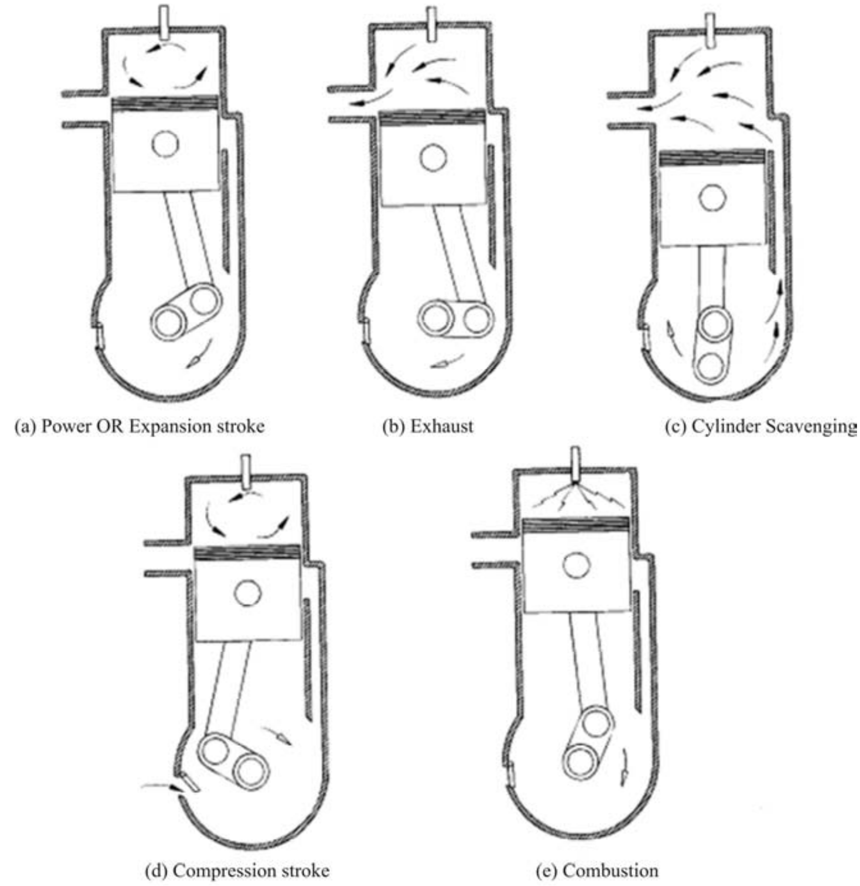

Fig. 1.4 2-Stroke SI Engine Operating Cycle

The theoretical indicator diagram for a two stroke cycle pertrol engines is shown in Fig. 1.5

Process 1-2: isentropic compression of the charge in the cylinder. The charge inside the cylinder is compressed and the piston moves from bottom dead center to top dead center. This comprises first stroke of the engine.

Process 2-3: combustion at constant volume. This process takes place as process of constant volume and increase in pressure. In this process spark is ignited by spark plug inside the cylinder and fuel is burnt.

Process 3-4: isentropic expansion. The burnt fuel exerts pressure and moves the piston to bottom dead center. The gas expands in this process. This comprises the second stroke and the power stroke of the engine.

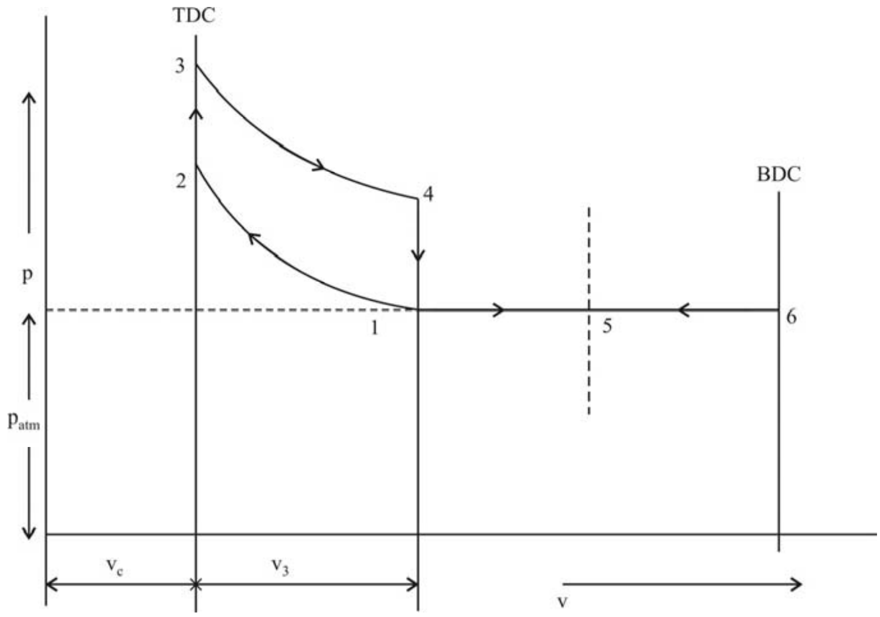

Fig. 1.5 Theoretical p-V Diagram of a Two Stroke Otto Cycle Engine

Process 4-1: Sudden release of burnt gases to the atmosphere as the exhaust port opens. This process takes place as process of constant volume and decrease in pressure. In this process, the burnt gas is exhausted outside the cylinder.

Process 1-6& 6-1: Sweeping out the exhaust gases to the atmosphere at the atmospheric pressure and charging the cylinder with charge.

Process 5-6 & 6-5: Charging the cylinder with charge through the transfer ports and scavenging through exhaust ports.

The point "5" indicates the opening of the inlet or transfer ports.

Also the compression of the charge starts from point "1" instead of point "6" Therefore, the effective stroke (compression stroke) is less than the actual stroke.

The actual indicator diagram for a two stroke cycle petrol engine is shown in Fig. 1.6. The section is shown by the line 1-2-3 (from the instant transfer port opens (TPO) and transfer port closes). During the section stage the exhaust port is also open. In the first half of suction stage, the volume of fuel-air mixture and burnt gases increases. This happens as the piston moves from 1 to 2. In the second half of suction stage, the volume of charge and burnt gases decreases. This happens as the piston moves upwards from 2 to 3. A little beyond 3, the exhaust port closes (EPC) at 4. Now the charge inside the engine cylinder is compressed which is shown by the line 4-5. At the end of compression, there is an increase in pressure inside the engine cylinder. Shortly before the end of compression, the charge is ignited with the help of spark plug as shown in Fig. 14 e. The sparking suddenly increases temperature and pressure of the product of combustion. But the volume, practically, remains constant as shown by the line 5-6. The expansion is shown by the line 6-7. Now the exhaust port opens at 7, and the burnt gases are exhausted into the atmosphere through the exhaust port. It reduces pressure. As the piston moving towards BDC, therefore volume of burnt gases increases from 7 to 1. At 1 the transfer port opens (TPN) and suction starts.

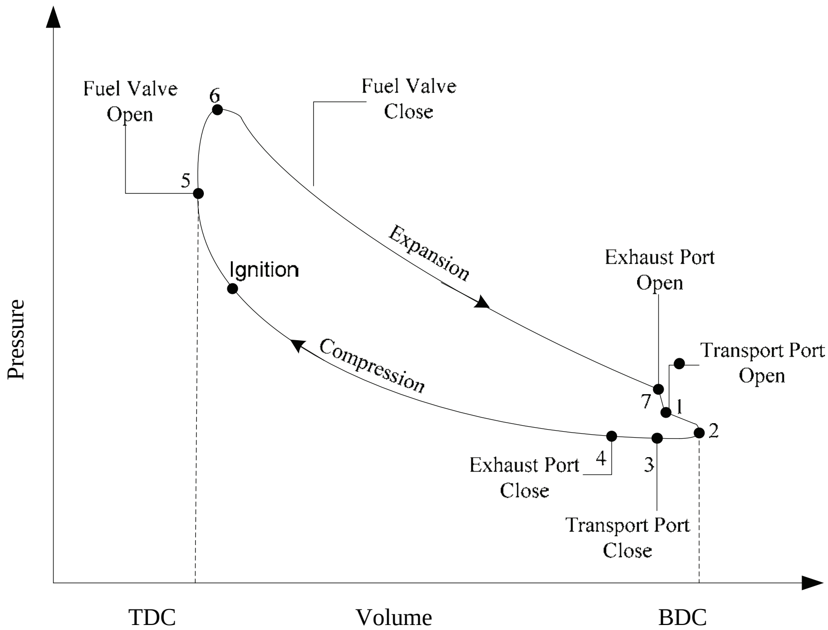

Fig. 1.6 Actual P-V Diagram of a Two Stroke Otto Cycle Engine

1.5.2 Working of 4-Stroke SI Engine

(i) ***First Stroke (Intake Stroke or Induction):*** The piston travels from TDC to BDC with the intake valve open and exhaust valve closed. This creates an increasing volume in the combustion chamber, which in turn creates a vacuum. The resulting pressure differential causes air to be pushed into the cylinder. As the air passes through the intake system, fuel is added to it in the desired amount by means of fuel injectors or a carburetor (Fig. 1.7(a)).

(ii) ***Second Stroke:*** Compression Stroke When the piston reaches BDC, the intake valve closes and the piston travels back to TDC with all valves closed. This compresses the air-fuel mixture, raising both the pressure and temperature in the cylinder. The finite time required to close the intake valve. Near the end of the compression stroke, the spark plug is fired and combustion is initiated (Fig. 1.7(b)).

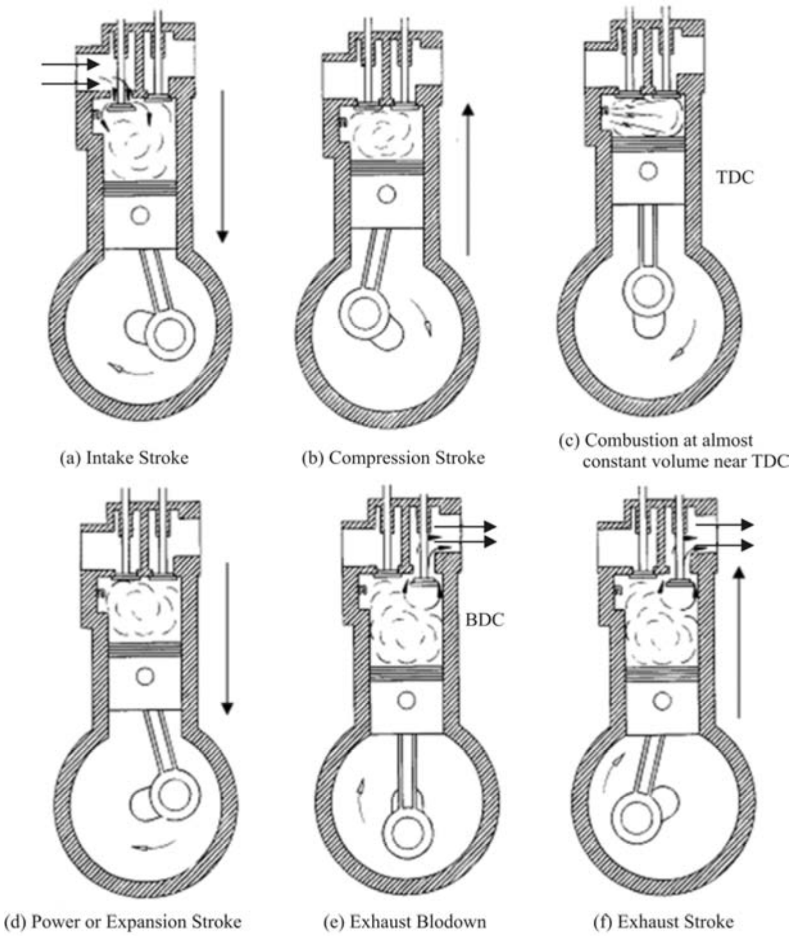

Fig. 1.7 4-Stroke SI Engine Operating Cycle

(iii) ***Combustion:*** Combustion of the air-fuel mixture occurs in a very short but finite length of time with the piston near TDC (i.e., nearly constant-volume combustion). It starts near the end of the compression stroke. Combustion changes the composition of the gas mixture to that of exhaust products and increases the temperature in the cylinder to a very high peak value. This, in turn, raises the pressure in the cylinder to a very high peak value (Fig. 1.7(c)).

(iv) ***Third Stroke (Expansion Stroke or Power Stroke):*** With all valves closed, the high pressure created by the combustion process pushes the piston away from TDC. This is the stroke which produces the work output of the engine cycle. As the piston travels from TDC to BDC, cylinder volume is increased, causing pressure and temperature to drop (Fig. 1.7(d)).

(v) ***Exhaust Blowdown:*** Late in the power stroke, the exhaust valve is opened and exhaust blowdown occurs. Pressure and temperature in the cylinder are still high relative to the surroundings at this point, and a pressure differential is created through the exhaust system which is open to atmospheric pressure. This pressure differential causes much of the hot exhaust gas to be pushed out of the cylinder and through the exhaust system when the piston is near BDC. This exhaust gas carries away a high amount of enthalpy, which lowers the cycle thermal efficiency. Opening the exhaust valve before BDC reduces the work obtained during the power stroke but is required because of the finite time needed for exhaust blowdown (Fig. 1.7(e)).

(vi) ***Fourth Stroke (Exhaust Stroke):*** By the time the piston reaches BDC, exhaust blowdown is complete, but the cylinder is still full of exhaust gases at approximately atmospheric pressure. With the exhaust valve remaining open, the piston now travels from BDC to TDC in the exhaust stroke. This pushes most of the remaining exhaust gases out of the cylinder into the exhaust system at about atmospheric pressure, leaving only that trapped in the clearance volume when the piston reaches TDC. Near the end of the exhaust stroke, the intake valve starts to open, so that it is fully open by TDC when the new intake stroke starts the next cycle. Near TDC the exhaust valve starts to close (Fig. 1.7(f)).

Theoretical indicator diagram for a four-stroke cycle petrol engine: In the above operation, the following assumption were made-

(i) Suction and exhaust take place at atmospheric pressure.

(ii) Suction and exhaust take place at 180^o rotation of crank.

(iii) Compression and expansion also take place at 180^o rotation of crank.

(iv) Compression and expansion are isentropic.

(v) The combustion takes place instantaneously at constant volume at the end of compression stroke.

(vi) Pressure suddenly falls to the atmospheric pressure at end of expansion stroke.

With these assumptions the working of 4-Stroke Otto cycle engine on p-V diagram as shown in Fig. 1.8.

Process 5-1 (Suction Stroke): In this process fresh air and fuel mixture i.e., charge is passed inside the cylinder. The piston moves from top dead center to bottom dead center. This comprises the first stroke of the engine.

Process 1-2 (Compression Stroke): In this process the charge is compressed and piston is moved to top dead center. This comprises the second stroke of the engine.

Process 2-3 (Instantaneous-Combustion): In this process spark plug ignites the spark and the fuel is burnt. This process is of constant volume and increase in pressure.

Process 3-4 (Expansion Stroke): In this process the burnt fuel expands itself and exerts pressure on the piston. The piston moves from top dead center to bottom dead center. This comprises the third stroke of the engine and the power stroke.

Process 4-1(**Sudden Fall in Pressure):** In this process the burnt gas is exhausted out and the pressure decreases with constant volume.

Process 1-5 (Exhaust Stroke): In this process the burnt gas is completely moved out of the cylinder by the action of piston. Piston moves from bottom dead center to top dead center. This comprises the fourth stroke of the engine.

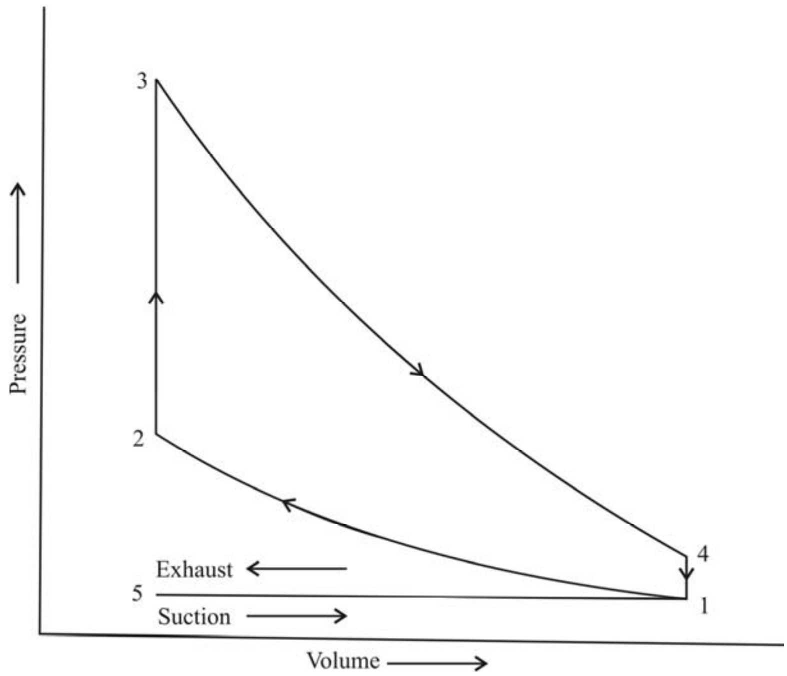

Fig. 1.8 Theoretical p-V Diagram of a Four-Stroke Otto Cycle Engine

Actual indicator (p-V) diagram for a four stroke cycle petrol cycle: In the above operations, all the ideal conditions are assumed but in practice, the actual conditions differ from the ideal as described below (Fig. 1.9).

(i) The suction of mixture in the cylinder is possible only if the pressure inside the cylinder is below atmospheric pressure.

(ii) The burnt gases can be pushed out into the atmosphere only if the pressure of the exhaust gases is above atmospheric pressure.

(iii) The combustion and expansion do not follow the isentropic law, as there will be heat exchange during process.

(iv) Sudden pressure rise is not possible after ignition as combustion take sometime for completion and actual pressure rise is less than theoretical considered. The pressure increase takes place through some crank rotation, or increase in volume.

(v) Sudden pressure release after the opening of expansion valve is not possible and also takes place through some crank rotation.

It may be noted that line 5-1 is below the atmospheric pressure line. This is due to the fact that owing to restricted area of the inlet passage the entering fuel mixture cannot cope with the speed of the piston. The exhaust line 4-5 is slightly above the atmospheric pressure line. This is due to the fact that owing to restricted area of the exhaust passage, which does not allow exhaust gases to leave the engine cylinder quickly.

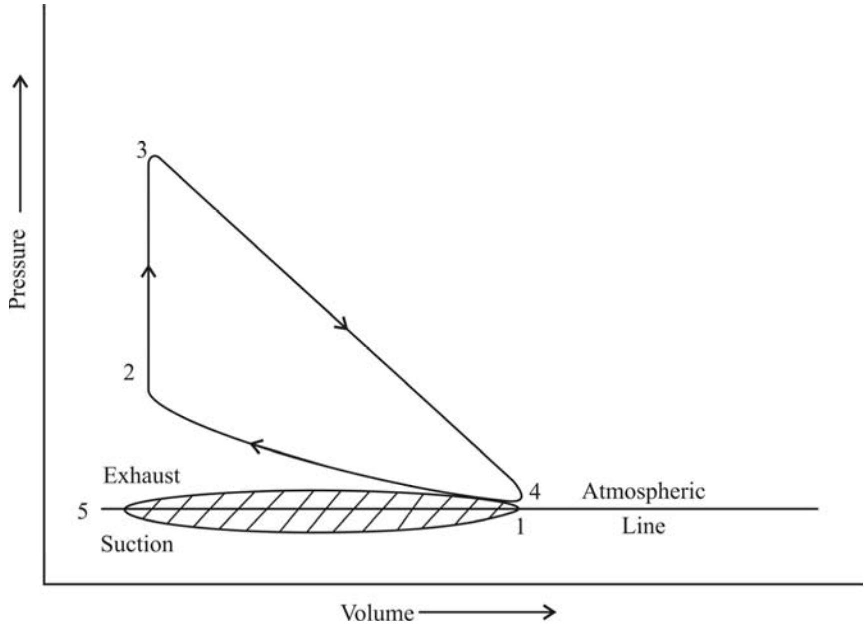

Fig. 1.9 Actual p-V Diagram of a Four-Stroke Otto Cycle Engine

The loop, which has area 4-5-1 is, called negative loop. It gives the pumping loss due to admission of fuel air mixture and removal of exhaust gases. The area 1-2-3-4 is the gross work (Fig. 1.9).

1.6 Compression Ignition Engine (Diesel Engine)

1.6.1 Working of 2-Stroke CI Engine

A two-stroke diesel engine (Fig. 1.10) shares the same operating principles as other internal combustion engines. It has all of the advantages that other diesel engines have over gasoline engines. A two-stroke diesel engine does not produce as much power as a four-stroke diesel engine; however, it runs smoother than the four-stroke diesel. This is because it generates a power stroke each time the piston moves downward; that is, once for each crankshaft revolution. The two-stroke diesel engine has a less complicated valve train because it does not use intake valves. Instead, it requires a supercharger to force air into the cylinder and to force exhaust gases out, because the piston cannot do this naturally as in four-stroke engines. The two-stroke diesel takes in air and discharges exhaust through a system called scavenging. Scavenging begins with the piston at bottom dead center. At this point, the intake ports are uncovered in the cylinder wall and the exhaust valve is open. The supercharger forces air into the cylinder, and, as the air is forced in, the burned gases from the previous operating cycle are forced out (Fig. 1.11).

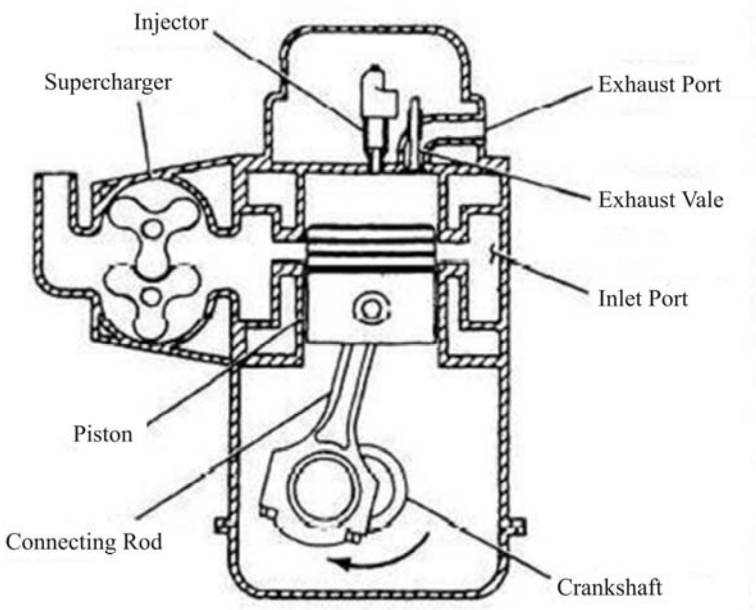

Fig. 1.10 Two-Stroke Cycle Diesel Engine

Compression Stroke: As the piston moves towards top dead center, it covers the intake ports. The exhaust valves close at this point and seals the upper cylinder. As the piston continues upward, the air in the cylinder is tightly compressed (Fig. 1.11). As in the four-stroke cycle diesel, a tremendous amount of heat is generated by the compression.

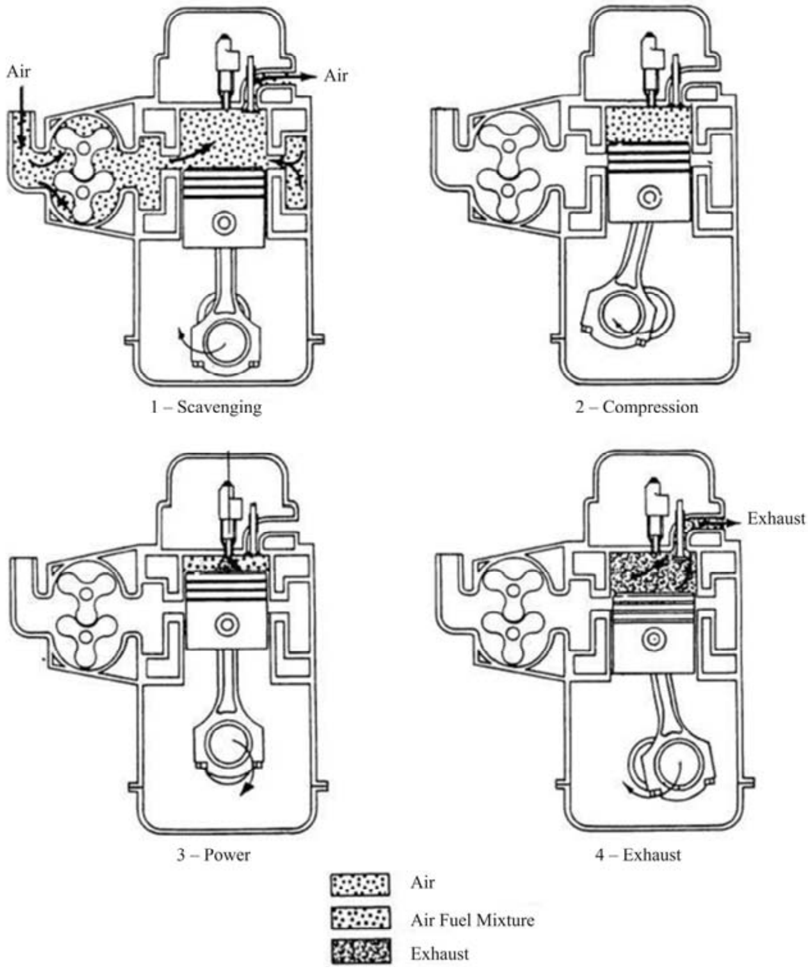

Fig. 1.11 Two-Stroke CI Engine Operating Cycle

Power Stroke: As the piston reaches top dead center, the compression stroke ends. Fuel is injected at this point and the intense heat of the compression causes the fuel to ignite. The burning fuel pushes the piston down, giving power to the crankshaft. The power stroke ends when the piston gets down to the point where the intake ports are uncovered. At about this point, the exhaust valve opens and scavenging begins again, as shown in Fig. 1.11.

Fig. 1.12 shows theoretical p-V diagram of two-stroke diesel cycle engine.

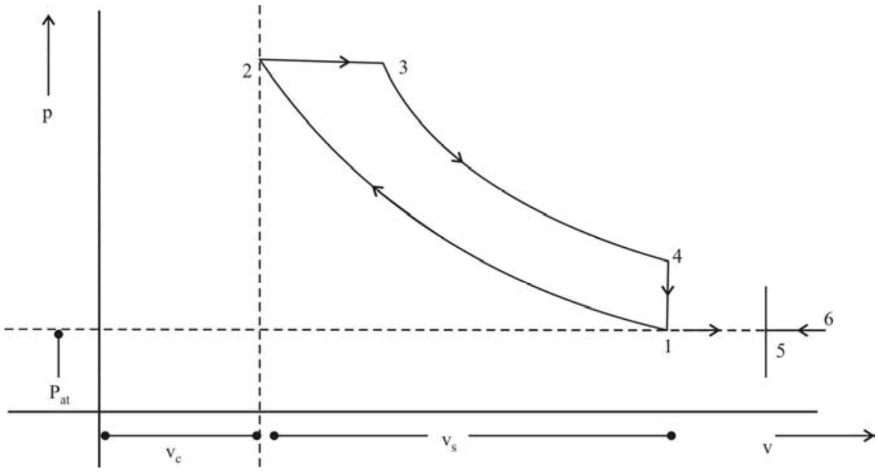

Fig. 1.12 Theoretical p-V Diagram of a Two Stroke Diesel Cycle Engine

Process 1-2: Isentropic compression of the air in the cylinder. The air inside the cylinder is compressed and the piston moves from bottom dead center to top dead center. This comprises the first stroke of the engine.

Process 2-3: Combustion at constant Pressure. In this process diesel is pumped inside the cylinder by the help of fuel pump and fuel is burnt.

Process 3-4: Isentropic Expansion of the burnt fuel in the cylinder. The burnt fuel exerts pressure and moves the piston to bottom dead center. The gas expands in this process. This comprises the second stroke and the power stroke of the engine.

Process 4-1: Sudden release of burnt gases to the atmosphere as the exhaust port opens. This process takes place as process of constant volume and decrease in pressure. In this process the burnt gas is exhausted outside the cylinder.

Process 1-6 & 6-1: Sweeping out the exhaust gases to the atmosphere.

Process 5-6 & 6-5: Charging the cylinder with fresh charge through the transfer ports and scavenging action takes place.

Fig. 1.13 shows the actual indicator diagram for a two stroke cycle diesel engine. The suction is shown by the line 1-2-3, from the instant transfer ports opens and transfer port closes. During the suction stage, the exhaust port is opens. In the first half of suction stage, the volume of air and burnt gases increases. This happens as the piston moves from 1-2. In the second half of the suction stage, the volume of air and burnt gases decreases. This happens as the piston moves upwards from 2-3. A little beyond 3, the exhaust port closes at 4. Now the air inside the engine cylinder is compressed which is shown by the line 4-5. At the end of compression there is an increases in pressure inside the engine cylinder, shortly before the end of compression, the fuel valve opens and the fuel is injected into the engine cylinder. The fuel is ignited by high temperature of the compressed air. The ignition suddenly increases volume and temperature of the products of combustion. But the pressure, practically, remains constant as shown by the line 5-6. The expansion is shown by the line 6-7. Now the exhaust port opens at 7, and the burnt gases are exhausted into the atmosphere through the exhaust port. It reduces pressure. As the piston moving towards BDC, therefore volume of burnt gases increases from 7 to 1. At 1 the transfer port opens (TPO) and suction starts.

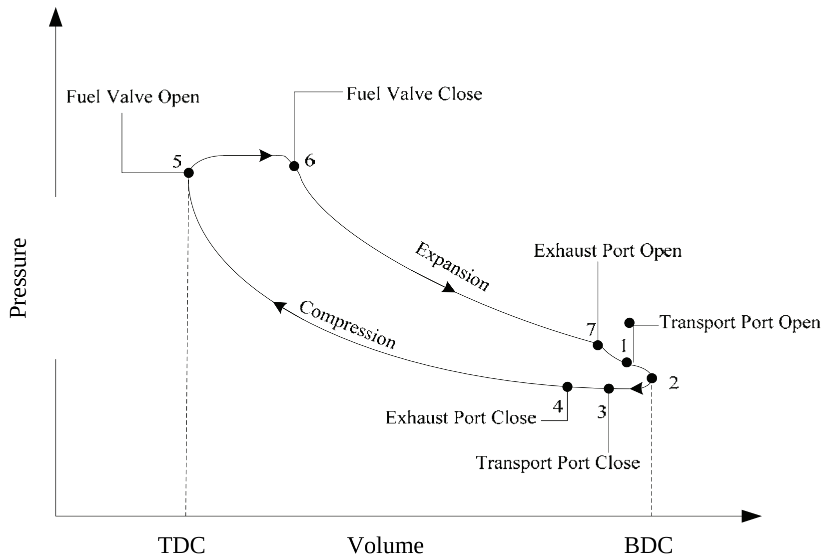

Fig. 1.13 Actual P-V Diagram of a Two Stroke Diesel Cycle Engine

1.6.2 Working of 4-Stroke Diesel Engine

Intake Stroke: The piston is at top dead center at the beginning of the intake stroke, and, as the piston moves downward, the intake valve opens. The downward movement of the piston draws air into the cylinder, and, as the piston reaches bottom dead center, the intake valve closes (Fig. 1.14(a)).

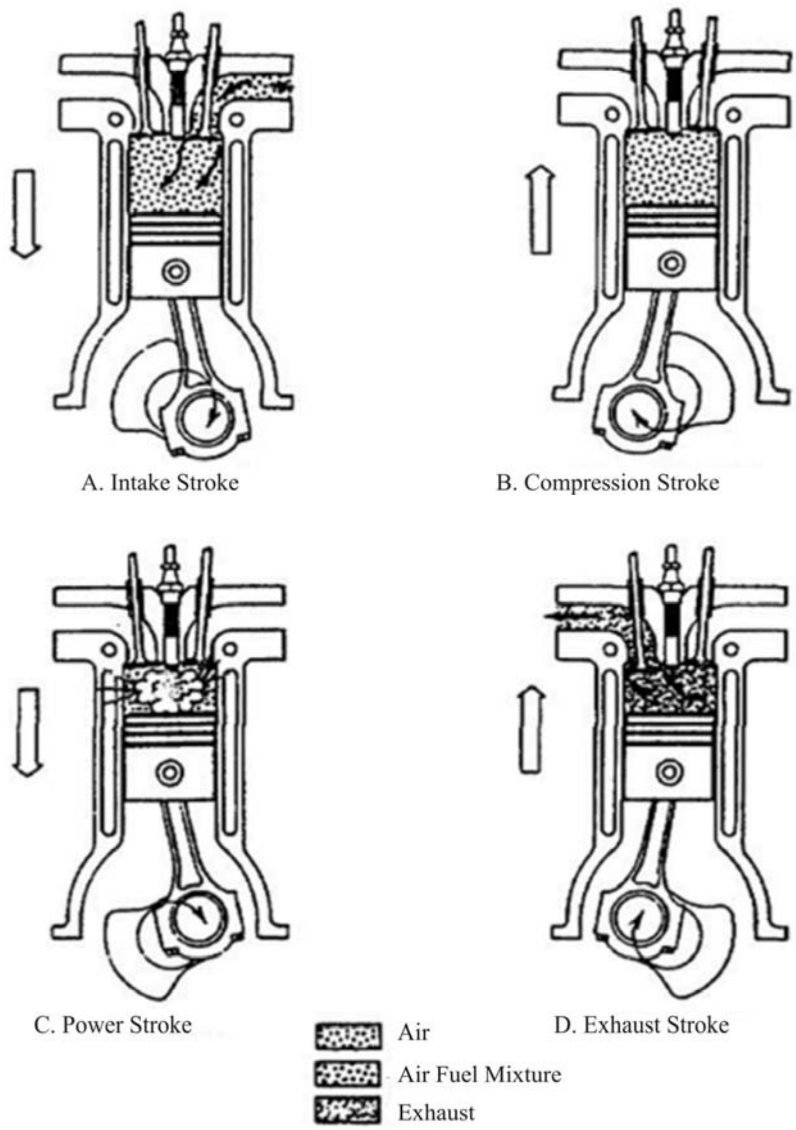

Figure 1.14 Four Stroke CI Engine Operating Cycle

Compression Stroke: The piston is at bottom dead center at the beginning of the compression stroke, and, as the piston moves upward, the air compresses. As the piston reaches top dead center, the compression stroke ends (Fig. 1.14(b)).

Power Stroke: The piston begins the power stroke at top dead center. The air is compressed to as much as 500 psi and at a compressed temperature of approximately 1000°F. At this point, fuel is injected into the combustion chamber and is ignited by the heat of the compression. This begins the power stroke. The expanding force of the burning gases pushes the piston downward, providing power to the crankshaft. The diesel fuel will continue to burn through the entire power stroke (a more complete burning of the fuel). The gasoline engine has a power stroke with rapid combustion in the beginning, but little to no combustion at the end (Fig. 1.14(c)).

Exhaust Stroke: As the piston reaches bottom dead center on the power stroke, the power stroke ends and the exhaust stroke begins. The exhaust valve opens, and, as the piston rises towards top dead center, the burnt gases are pushed out through the exhaust port. As the piston reaches top dead center, the exhaust valve closes and the intake valve opens. The engine is now ready to begin another operating cycle (Fig. 1.14(d)).

Working of the four stroke CI engine cycle on p-V diagram as shown in Fig. 1.15.

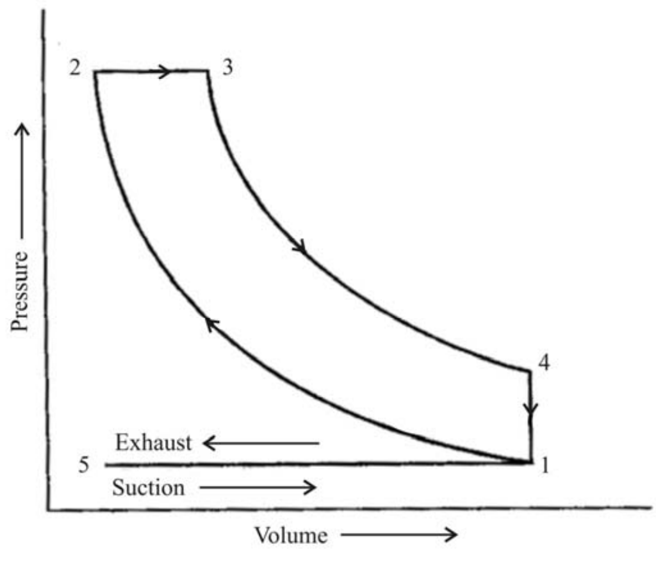

Fig. 1.15 Theoretical p-V Diagram of a Four Stroke Diesel Cycle Engine

Process 5-1: In this process fresh air is passed inside the cylinder. The piston moves from top dead center to bottom dead center. This comprises the first stroke of the engine.

Process 1-2: In this process the air is compressed and piston is moved to top dead center. This comprises the second stroke of the engine.

Process 2-3: In this process diesel is pumped into the cylinder through fuel pump and the fuel is burnt. This process is of constant volume and increase in pressure.

Process 3-4: In this process the burnt fuel expands itself and exerts pressure on the piston. The piston moves from top dead center to bottom dead center. This comprises the third stroke of the engine and the power stroke.

Process 4-1: In this process the burnt gas is exhausted out and the pressure decreases with constant volume.

Process 1-5: In this process the burnt gas is completely moved out of the cylinder by the action of piston. Piston moves from bottom dead center to top dead center. This comprises the fourth stroke of the engine.

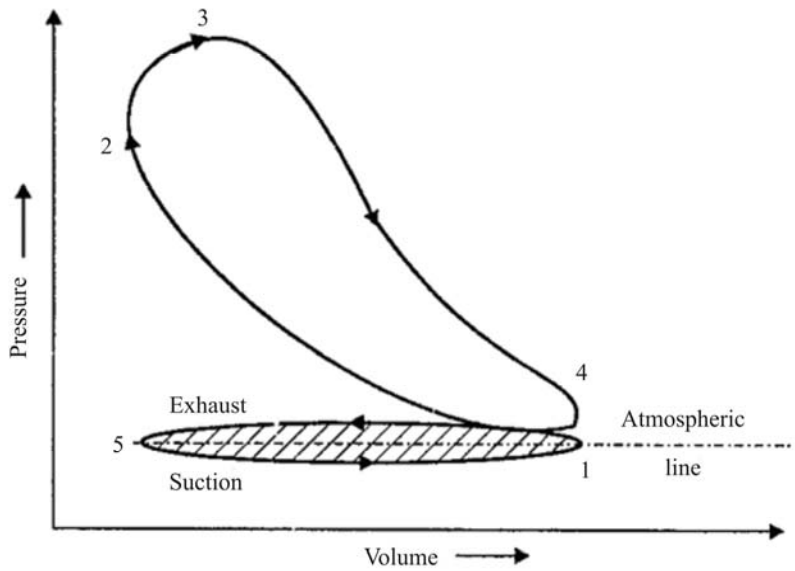

Fig. 1.16 Actual P-V Diagram of a Four Stroke Diesel Cycle Engine

The actual indicator diagram of 4-stroke cycle diesel engine has been shown in Fig. 1.16. The suction stroke is shown by line 1-2 which lies below the atmospheric pressure line. This pressure difference makes the fresh air to flow into the engine cylinder. The inlet valve offers some resistance to the incoming air. That is why, the air can not enter suddenly into the engine cylinder. As a result of this, pressure inside the cylinder remains somewhat below the atmospheric pressure during the suction stroke. The compression stroke is shown by the line 2-3, which shows that the inlet valve closes a little beyond 2 (i.e., B.D.C.). At the end of this stroke, there is an increase of pressure inside the engine cylinder, shortly before the end of the compression stroke (i.e., T.D.C.), fuel valve opens and the fuel is injected into the engine cylinder. The fuel is ignited by the temperature of the compressed air. The ignition suddenly increases volume and temperature of the products of combustion. But the pressure, practically remains constant. The expansion stroke is shown by the line 4-5 in which the exit valve opens a little before 5 (i.e., B.D.C.). Now the burnt gases are exhausted into the atmosphere through the exhaust valve, shown by 5-1, lies above atmospheric pressure line. The exhaust valve offers some resistance to the outgoing burnt gases. That is why, the burnt gases can not escape suddenly from the engine cylinder. As a result of this pressure inside the cylinder remains above the atmospheric pressure during the exhaust stroke.

1.7 Comparison of Spark Ignition (S.I.) and Compression Ignition (C.I.) Engines

The most prominent difference between Spark Ignition (SI) and Compression Ignition (CI) engines is the type of fuel used in each. In SI engines petrol or gasoline is used as fuel, hence these engines are also called petrol engines. In CI engines diesel is used as fuel, hence they are also called diesel engines. Here are some other major differences between the SI and CI engines is given in Table 1.2.

Table 1.2 Comparison of Spark Ignition (S.I.) and Compression Ignition (C.I.) Engines

S. No	Features	S.I. Engines	C.I. Engines
1.	Thermodynamic Cycle	Otto cycle	Diesel cycle for slow speed engines. Dual cycle for high speed engines.
2.	Fuel used	Petrol (Gasoline)	Diesel
3.	Air fuel (A/F) ratio	10:1 to 20:1	18:1 to 100:1
4.	Compression Ratio	Up to 11; Average value 7 to 9 Upper limit fixed by anti-knock quality of fuel.	Up to12 to 24; Average value 15 to 18; Upper limit is limited by thermal and mechanical stresses.

Table 1.2 ***Contd…***

S. No	Features	S.I. Engines	C.I. Engines
5.	Combustion	Spark Ignition	Compression Ignition
6.	Fuel Supply	By Carburetor (Low Cost)	By injection (High Cost)
7.	Operating pressure 1. Compression pressure 2. Maximum Pressure	7 bar to 15 bar 45 bar to 60 bar	30 bar to 50 bar 60 bar to 120 bar
8.	Operating Speed	High speed: 2000 to 6000 r.p.m	Low speed: 400 r.p.m Medium speed: 400 to 1200 r.p.m. High speed: 1200 to 3500 r.p.m
9.	Power Control	Throttle governed the quantity	Rack governed the quantity
10.	Calorific value	44 MJ/kg	42 MJ/kg
11.	Cost of running	High	Low
12.	Maintenance cost	Minor maintenance	Major over all require
13.	Super charging	Limited by detonation. Used only in aircraft engines.	Limited by lower power and mechanical and thermal stresses. Widely used.
14.	Two stroke operation	Less suitable, fuel loss in scavenging. But small two stroke engines are used in mopeds, scooters and motor cycles due to their simplicity and low cost.	No fuel loss in scavenging. More suitable.
15.	High powers	No	Yes
16.	Distribution of fuel	A/F ratio is not optimum in multi cylinder engines.	Excellent distribution of fuel in multi cylinder engines.
17.	Starting	Easy, low cranking effort.	Difficult, high cranking effort.
18.	Exhaust gas temperature.	High, due to low thermal efficiency	Low, due to high thermal efficiency.
19.	Weight per unit power	Low (0.5 to 4.5 kg/kW)	High (3.3 to 13.5 kg/kW)

Table 1.2 ***Contd…***

S. No	Features	S.I. Engines	C.I. Engines
20.	Initial capital Cost	Low	High due to heavy weight and study construction; costly construction 1.25-1.5 times.
21.	Noise and distribution	Less	More idle noise problem
22.	Applications	Mopeds, Scooters, motorcycles, Simple engine passenger cars	Buses, trucks, locomotives, tractors, earth moving machinery and stationary generating plants.

1.8 Comparison between 2-Stroke and 4-Stroke Engines

The two-stroke engine was developed to obtain a greater output from the same size of the engine. The engine mechanism also eliminates the valve arrangement making it mechanically simpler. Almost all two-stroke engines have no conventional valves but only ports (some have an exhaust valve). This simplicity of the two-stroke engine makes it cheaper to produce and easy to maintain. Theoretically a two-stroke engine develops twice the power of a comparable four stroke engine because of one power stroke every revolution (compared to one power stroke every two revolutions of a four-stroke engine). This makes the two-stroke engine more compact than a comparable four-stroke engine. In actual practice power output is not exactly doubled but increased by only about 30% because of

(i) Reduced effective expansion stroke and

(ii) Increased heating caused by increased number of power strokes that limits the maximum speed.

The other advantages of the two-stroke engines are more uniform torque on crankshaft and comparatively less exhaust gas dilution. However, when applied to the spark-ignition engine the two stroke cycle has certain disadvantages which have restricted its application to only small engines suitable for motor cycles, scooters, lawn mowers, outboard engines etc. In the SI engine, the incoming charge consists of fuel and air. During scavenging, as both inlet and exhaust ports are open simultaneously for some time, there is a possibility that some of the fresh charge containing fuel escapes with the exhaust. This results in high fuel consumption and lower thermal efficiency. The other drawback of two-stroke engine is the lack of flexibility, viz., the capacity to operate with the same efficiency at all speeds. At part throttle operating condition, the amount of fresh mixture entering the cylinder is not enough to clear all the exhaust gases and a part of it remains in the cylinder to contaminate the charge. This results in irregular operation of the engine. The two-stroke diesel engine does not suffer from these defects. There is no loss of fuel with exhaust gases as the intake charge in diesel engine is only air. The two-stroke diesel engine is used quite widely. Many of the high output diesel engines work on this cycle. A disadvantage common to all two-stroke engines, gasoline as well as diesel, is the greater cooling and lubricating oil requirements due to one power stroke in each revolution of the crankshaft. Consumption of lubricating oil is high in two-stroke engines due to higher temperature. A detailed comparison of two-stroke and four-stroke engines are given in the Table below.

Table 1.3 Comparison of two-stroke and four-stroke engines

S.No	Features	Four Stroke Cycle Engines	Two Stroke Cycle Engines
1.	Completion of cycle	The cycle is completed in four strokes of the piston or in two revolutions of the crank shaft. Thus one power stroke is obtained in every two revolutions of the crank shaft.	The cycle is completed in two strokes of the piston or in one revolution of the crank shaft. Thus power stroke is obtained in each revolutions of the crank shaft.
2.	Flywheel required heavier or lighter	Because of the turning movement is not so uniform and hence heavier flywheel is needed.	More uniform turning movements and hence lighter flywheel is needed.
3.	Power produced for same size of engine	Again because of one power stroke for two revolutions, power produced for same size of engine is small or for the same power the engine is heavy and bulky.	Because of one power stroke for one revolution. power produced for same size of engine is more (Theoretically twice, actually about 1.3 times) or for the same power the engine is light and compact.

Table 1.3 ***Contd…***

S.No	Features	Four Stroke Cycle Engines	Two Stroke Cycle Engines
4.	Cooling and lubrication requirements	Because of one power stroke in two revolutions lesser cooling and lubrication requirements. Lesser rate of wear and tear.	Because of one power stroke in one revolutions greater cooling and lubrication requirement. Large rate of wear and tear.
5.	Valve and valve mechanism	The four stroke engine contains valve and valve mechanism.	Two stroke engines have no valves but only ports (some two stroke engines are fitted with conventional exhaust valves).
6.	Initial cost	Because of heavy weight and complication of valve mechanism, the initial cost is higher.	Because of light weight and simplicity due to absence of valves mechanism, cheaper in initial cost.
7.	Volumetric efficiency	Volumetric efficiency more due to more time of induction.	Volumetric efficiency less due to lesser time for induction.
8.	Thermal and part load efficiency	Thermal efficiency higher, part load efficiency better than two stroke cycle engine.	Thermal efficiency lower, part load efficiency lesser than four stroke cylinder engine.
9.	Applications	Used where efficiency is important; in cars, buses, trucks, tractors, industrial engines, aeroplane, power generators etc.	In two strokes petrol engine some fuel is exhausted during scavenging. Used where (a) low cost, and (b) compactness and light weight important. Two stroke (air cooled) petrol engines used in very small sizes only, lawn movers, scooters, motor cycles (lubrication oil mixed with petrol). Two stroke diesel engines used in very large sizes more than 60 cm bore, for ship propulsion because of low weight and compactness.

1.9 Thermodynamic Cycles

1.9.1 Carnot Cycle

Nicolas Leonard Sadi Carnot was the first to provide a thermodynamic model of a heat engine, abstracting from the only available heat engine, the steam engine, to pinpoint the fundamentals: the idea of a generic working fluid, performing a generic cyclic process, interacting with generic heat reservoirs. In that his only publication, Carnot concluded that all heat engines where limited in their energy-conversion efficiency by the operating temperatures, and that the maximum efficiency is obtained when the working fluid is assumed to follow four ideal processes (Fig. 1.17):

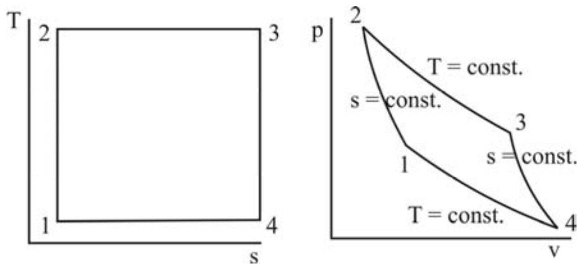

Fig. 1.17 The Carnot Cycle in T-s and p-V Diagrams

- An isentropic compression (1 to 2), to change temperature without heat transfer.
- An isothermal heat input (2 to 3), from the hot source, at the hot-source temperature.
- An isentropic expansion (3 to 4), to change temperature without heat transfer.
- An isothermal heat rejection to the cold source (usually the environment), at the cold-source temperature.

Carnot reached those conclusion by a set of rational deductions, namely: any engine with friction would have less efficiency than one without, among all engines exchanging heat at different temperatures, the one with highest efficiency only exchanges heat at the two extreme temperatures (the hottest and the coldest), and all reversible engines working with the same couple of temperature extremes have the same efficiency.

The energy can be easily deduced by establishing the overall energy conservation, ΔE_{univ} = $Q_{hot}WQ_{cold}$ = 0, and the overall entropy balance, $\Delta S_{uni}Q_{hot}/T_{hot}+Q_{cold}/T_{cold}$, ≥ 0, the latter being zero in the ideal case of a Carnot cycle, what yields:

$$\eta_e \equiv \frac{W_{net}}{Q_{pos}} \rightarrow \eta_{e.Carrot} = 1 - \frac{T_1}{T_2}$$

Carnot cycle, and any other conceivable power cycle, is to be run clockwise in both the T-s and *p-V* thermodynamic diagrams, since the heat engine receives net heat, that in a reversible process is $Q_{net} = \int T dS$ (recall the area interpretation of integrals), and delivers net work, that in a reversible process is $W_{net} = \int pdV$; notice that in a cycle $\int dU = \int Td\tilde{S} \int pdV = 0$.

The Carnot cycle is not practical, not only because of unavoidable frictional losses (could be minimised with appropriate lubrication), but because of the heat transfer with negligible temperature jump, that would render the heat transfer rate infinitesimal for a finite size engine with finite thermal transmittance with the heat sources.

1.9.2 Otto Cycle

The Otto cycle is a first approximation to model the operation of a spark-ignition engine, first built by Nikolaus Otto in 1876, and used in many cars, small planes and small power systems.

In the ideal air-standard Otto cycle, the working fluid is just air, which is assumed to follow four processes: isentropic compression, constant-volume heat input from the hot source, isentropic expansion, and constant-volume heat rejection to the environment (Fig. 1.18).

The main parameters of ideal and real Otto cycles are:

(i) Size, measured by the displacement volume (the volume swept by the piston, V_1-V_2), usually less than 0.5 litres per cylinder, to avoid self-ignition.

(ii) Speed, more precisely crankshaft speed, *n*, with a typical operation range n = 1000-7000 rpm (n = 20-120 Hz). The maximum value may be in the range n_{max}= 6000-8000 rpm for four-stroke engines. Two-stroke motorcycle engines run quicker (n_{max} = 13 000 rpm), the quickest (n_{max} = 20 000 rpm) being the smallest engines (two stroke), used in aircraft modelling.

(iii) Compression ratio, $r = V_1/V_2$, with a typical range of r = 8-10 (up to 14 in direct-injection spark-ignition engines), limited by the knock or self-ignition problem.

(iv) Mean effective pressure, p_{mep}, defined as the unit work divided by the displacement, with a typical range of 0.2-1.5 MPa (the full-load value may range from p_{mep} = 1.2 MPa in two-stroke motorcycle engines, to p_{mep} = 1.7 MPa in the largest turbocharged engines). Maximum pressure may have a typical range of 4-10 MPa. Performance maps of reciprocating engines are usually presented on p_{mep} Vs N diagram, i.e., mean effective pressure versus engine speed.

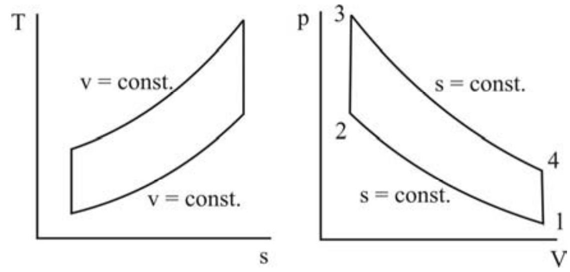

Fig. 1.18 The Ideal Otto Cycle in the T-s and p-V Diagram

The cold-air-standard model takes as working fluid air with constant properties (those at the inlet, i.e. cold), what renders the analysis simple. The energy exchanges for the trapped control mass, *m*, are $W_{12}/m = c_v (T_2 - T_1)$, $Q_{12} = 0$, $W_{23} = 0$, $Q_{23}/m = c_v(T_3 - T_2)$, $W_{34}/m = c_v(T_4 - T_3)$, $Q_{34} = 0$, $W_{41} = 0$, $Q_{41}/m = c_v(T_1 - T_4)$, and the energy efficiencies is:

$$\eta_{e,Otto} = \frac{W_{34} - W_{12}}{Q_{23}} = \frac{(T_3 - T_4) - (T_2 - T_1)}{T_3 - T_2} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{\gamma - 1}}$$

where, $\gamma = c_p/c_v$, 1.4 approx (for air)

Typical energy efficiencies of these engines are low, 25% to 35% when running at nominal power, and much lower at partial load (the main air flow is strangulated), but the engine is light, very powerful and responsive (accelerates very quickly).

One of the key advantages of Otto engines, is that cheap materials can be used in their construction (e.g., cast iron, against very expensive nickel alloys in gas turbines), because peak temperatures (up to 3000 K) are only realised within the burning gases and for short times, with an average temperature during the whole cycle of some 700 K, which would be the quasi-steady temperature level at the wall. Pollutant emission is higher because premixed fuel cannot burn close to the walls (the effect of walls is smaller in larger diesel engines, and most of the nearby gas is just non-premixed air), making the exhaust catalyser an environmental need.

1.9.3 Diesel Cycle

The Diesel cycle is a first approximation to model the operation of a compression-ignition engine, first built by Rudolf Diesel in 1893, and used in most cars, nearly all trucks, nearly all boats, many locomotives, some small airplanes, and many large electric power systems and cogeneration systems. It is the reference engine from 50 kW to 50 MW, due to the fuel used (cheaper and safer than gasoline) and the higher efficiency.

In the ideal air-standard Diesel cycle, the working fluid is just air, which is assumed to follow four processes (Fig. 1.19): isentropic compression, constant-pressure heat input from the hot source, isentropic expansion, and constant-volume heat rejection to the environment.

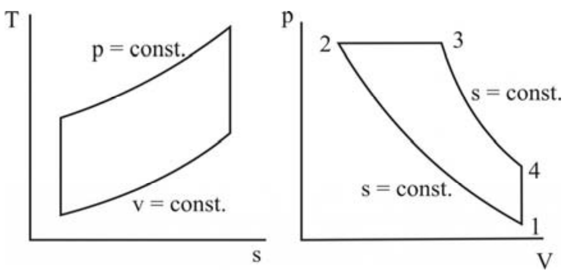

Fig. 1.19 The Ideal Otto Cycle in the T-s and p-V Diagram

Similarly to the Otto cycle, the main parameters of ideal and real Diesel cycles are also the size, measured by the displacement volume (that may reach more than 1 m^3 per cylinder in large marine engines), the compression ratio, $r = V_1/V_2$ (with a typical range of 16-22, limited just by strength), the cut-off ratio, r_c, or the mean effective pressure (in the range 1-2 MPa), or the maximum pressure (in the range of 3 MPa to 20 MPa), and the speed (with a typical range of 100-6000 rpm). The energy efficiency can be expressed as:

$$\eta_{e,Diesel} = 1 - \frac{1}{r^{\gamma-1}} \frac{r_c^{\gamma} - 1}{\gamma(r_c - 1)}$$

Typical energy efficiencies are from 30% to 54% (based on the lower heating value of the fuel). Real compression-ignition engines take ambient air (often after a first stage compression) and compress it (inside the cylinder) so much, rising the temperature accordingly, that the fuel burns as it is injected (after a small initial delay due to vaporisation and combustion kinetics).

One of its key advantages compared to Otto engines is the great load increase per cylinder associated to the higher pressures allowed (the mixture of fuel and air would deonate in Otto engines at high compressions), and the further load increase associated to charging previously-compressed air (turbocharging). Another advantage is the much better performance at part load, since there it is achieved by injecting less fuel instead of by throttling, and the torque (power divided per angular speed), changes less with angular speed.

Table 1.4 Comparison between Otto and Diesel Cycle

Otto Cycle	Diesel Cycle
Petrol engine works on Otto cycle	Diesel engine works on Diesel cycle
During suction stroke, air petrol mixture is sucked into the cylinder.	During suction stroke, only air is sucked into the cylinder.
Heat is added at constant volume.	Heat is added at constant pressure.
Efficiency is higher, for the same compression ratio	Efficiency is low, for the same compression ratio
Compression ratio has to be kept below 12 due to knocking	No limitation
Thermal efficiency is lower due to lower CR.	Thermal efficiency is higher due to higher CR.

Review Questions

1. Draw the Otto cycle on p-V diagram.
2. What is carnot cycle and its importance?
3. What is indicator diagram?
4. Why scavenging is important in two stroke engines compared to four stroke engines
5. Write any four advantage of 4 stroke petrol engine over 2 stroke petrol engine.
6. Write the air standard efficiency of an Otto cycle.
7. Compare four stroke and two stroke cycle engines and bring out their relative merits and demerits.
8. Explain with neat sketches the two different types of two stroke engines
9. Discuss the two stroke engine construction and operation with neat sketches
10. Briefly explain the principle of four stroke petrol engine with a simple sketch
11. Draw the ideal and actual indicator diagram for a four stroke petrol engine and explain why they differ each other.
12. What are the advantage and disadvantage of 2 stroke engine?
13. What is thermodynamic cycle?
14. What are the assumptions made for air standard cycle analysis?
15. Mention the various process of diesel cycle.
16. Sketch Otto cycle on p-V diagram and name all the process.
17. Plot and explain briefly the Diesel cycle on p-V & T-s diagram.
18. Write down the comparison between the S.I engine and C.I engine.
19. Define the following terms.
    1. Compression ratio
    2. Cut off ratio
    3. Expansion ratio.

20. Name the factors that affect air standard efficiency of Diesel cycle?
21. For the same compression ratio and heat supplied, state the order of decreasing air standard efficiency of Otto and diesel.
22. What is the range of compression ratio for Otto and Diesel cycle?
23. Differentiate between the auto cycle and diesel cycle.