Unit – I

Syllabus:

Gas power cycles: Otto, diesel, dual combustion cycles, description and representation on P-v and T-s diagram, thermal efficiency, mean effective pressure on air standard basis- comparison of cycles, Brayton cycle

- Evaluate thermal efficiency of Otto, diesel, dual cycle and Brayton cycle and they can represent on P-v and T-s diagrams
- Compare various gas power cycles
- Understand vapour power cycles
- Understand refrigeration cycles
- Evaluate performance of refrigeration cycles

- **Air-Standard Assumptions**

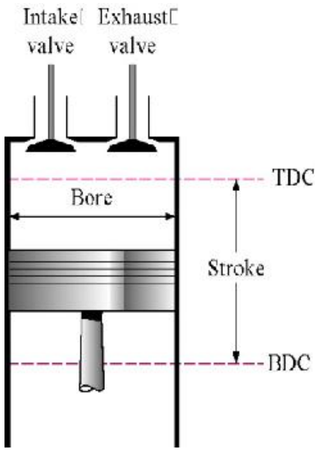
  In our study of gas power cycles, we assume the working fluid is air, and the air undergoes a thermodynamic cycle even though the working fluid in the actual power system does not undergo a cycle.

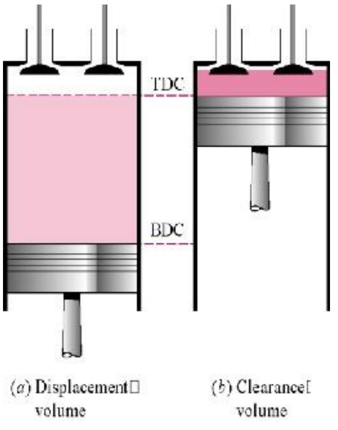
  To simplify the analysis, we approximate the cycles with the following assumptions:

  - The air continuously circulates in a closed loop and always behaves as an ideal gas.
  - All the processes that make up the cycle are internally reversible.
  - The combustion process is replaced by a heat-addition process from an external source.
  - A heat rejection process that restores the working fluid to its initial state replaces the exhaust process.
  - The cold-air-standard assumptions apply when the working fluid is air and has constant specific heat evaluated at room temperature (25°C or 77°F).

- **Terminology for Reciprocating Devices**

  The following is some terminology we need to understand for reciprocating engines—typically piston-cylinder devices. Let's look at the following figures for the definitions of top dead center (TDC), bottom dead center (BDC), stroke, bore, intake valve, exhaust valve, clearance volume, displacement volume, compression ratio, and mean effective pressure.



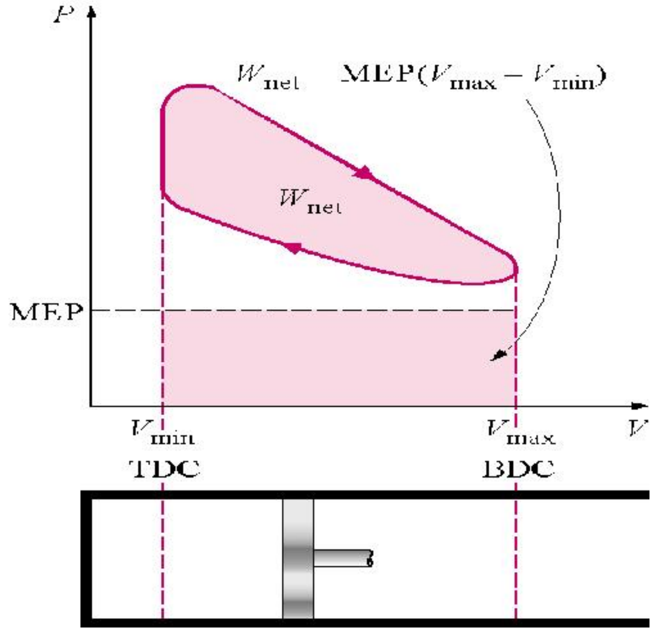


- The compression ratio r of an engine is the ratio of the maximum volume to the minimum volume formed in the cylinder.

$$r = \frac{V\max}{V\min} = \frac{V_{BDC}}{V_{TDC}}$$

- The mean effective pressure **(MEP)** is a fictitious pressure that, if it operated on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}}$$



- **Otto Cycle (Constant Volume Cycle):**

This ideal heat engine cycle was proposed in 1862 by Bean de Rochas. In 1876 Dr. Otto designed an engine to operate on this cycle. The Otto engine immediately became so successful from a commercial stand point, that its name was affixed to the cycle used by it.

The ideal p - v and T-s diagrams of this cycle are shown in fig. In working out the air-standard efficiency of the cycle, the following assumptions are made:

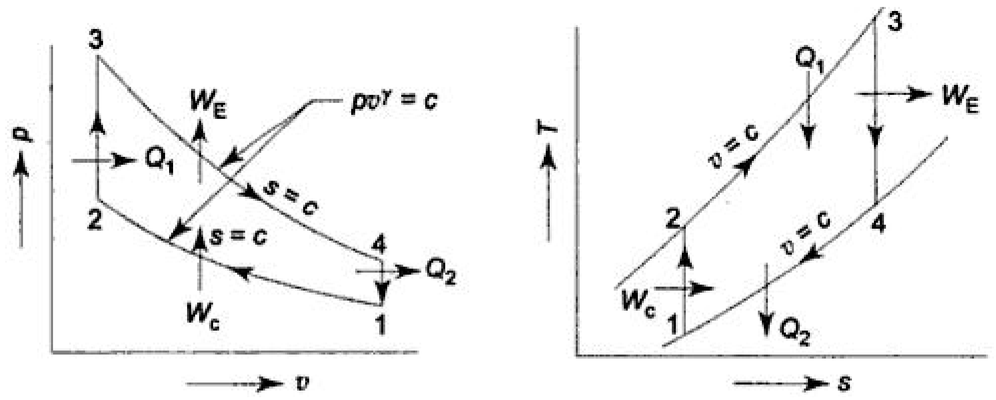
(i) The working fluid (working substance) in the engine cylinder is air, and it behaves as a perfect gas, i.e., it obeys the gas laws and has constant specific heats.

(ii) The air is compressed adiabatically (without friction) according to law $pv^{\gamma} = C$

(iii) The heat is supplied to the air at constant volume by bringing a hot body in contact with the end of the engine cylinder.

(iv) The air expands in the engine cylinder adiabatically (without friction) during the expansion stroke.

(v) The heat is rejected from the air at constant volume by bringing a cold body in contact with the end of the engine cylinder.



Process 1→ 2 Isentropic compression
Process 2 → 3 Constant volume heat addition
Process 3 → 4 Isentropic expansion
Process 4 → 1 Constant volume heat rejection

Consider one kilogram of air in the engine cylinder at point (1). This air is compressed adiabatically to point (2), at which condition the hot body is placed in contact with the end of the cylinder. Heat is now supplied at constant volume, and temperature and pressure rise; this operation is represented by (2-3). The hot body is then removed and the air expands adiabatically to point (4). During this process, work is done on the piston. At point (4), the cold body is placed at the end of the cylinder. Heat is now rejected at constant volume, resulting in drop of temperature and pressure. This operation is represented by (4-1). The cold body is then removed after the air is brought to its original state (condition). The cycle is thus completed. The cycle consists of two constant volume processes and two reversible adiabatic processes. The heat is supplied during constant volume process (2-3) and rejected during constant volume process (4-1). There is no exchange of heat during the two reversible adiabatic processes (1-2) and (3-4).

The performance is often measured in terms of the cycle efficiency.

$$\eta_{th} = \frac{W_{net}}{Q_{in}}$$

Thermal Efficiency of the Otto cycle

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Now to find Q_{in} and Q_{out}.

Apply first law closed system, V = constant.

Heat supplied during constant volume operation (2-3), Heat rejected during constant volume operation (4-1) is

$$q_{in} = u_3 - u_2 = c_v (T_3 - T_2)$$
$$q_{out} = u_4 - u_1 = c_v (T_4 - T_1)$$

$$Q_{net,23} = \Delta U_{23}$$
$$Q_{net,23} = Q_{in} = mC_v (T_3 - T_2)$$

$$Q_{net,41} = \Delta U_{41}$$
$$Q_{net,41} = -Q_{out} = mC_v (T_1 - T_4)$$
$$Q_{out} = -mC_v (T_1 - T_4) = mC_v (T_4 - T_1)$$

The thermal efficiency becomes

$$\eta_{th,Otto} = 1 - \frac{Q_{out}}{Q_{in}}$$
$$= 1 - \frac{mC_v (T_4 - T_1)}{mC_v (T_3 - T_2)}$$

$$\eta_{th,Otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$
$$= 1 - \frac{T_1 (T_4 / T_1 - 1)}{T_2 (T_3 / T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma - 1} = \left(\frac{v_3}{v_4}\right)^{\gamma - 1} = \frac{T_4}{T_3}$$

Since $V_3 = V_2$ and $V_4 = V_1$

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$
$$or$$
$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

The Otto cycle efficiency becomes

$$\eta_{th,Otto} = 1 - \frac{T_1}{T_2}$$

Since process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = \left(\frac{1}{r}\right)^{\gamma - 1}$$

Where the compression ratio is

$$r = \frac{v_{\max}}{v_{\min}} = \frac{v_1}{v_2}$$

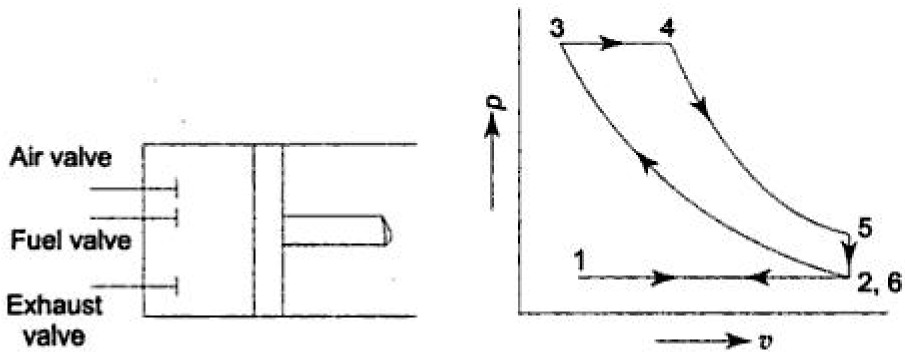
$$\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}$$

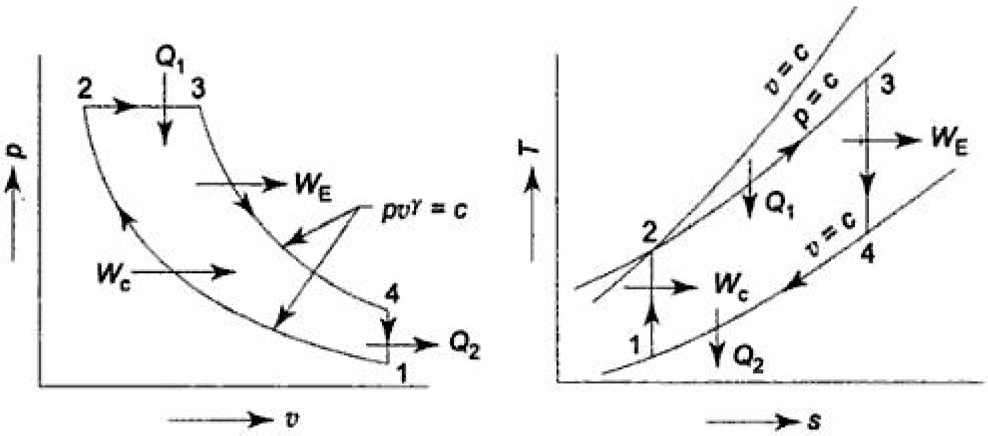
- **Air-Standard Diesel Cycle (or constant pressure cycle):**

The air-standard Diesel cycle is the ideal cycle that approximates the Diesel combustion engine

Process	Description
1-2	isentropic compression
2-3	Constant pressure heat addition
3-4	isentropic expansion
4-1	Constant volume heat rejection

The *P*-*v* and *T*-*s* diagrams are





$$Heat\ supplied = Q_1 = Q_{2-3} = mc_p(T_3 - T_2)$$

$$Heat\ \text{Rejected} = Q_2 = Q_{4-1} = mc_v(T_4 - T_1)$$

$$\text{Effieciency} = \eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_4 - T_1)}{mc_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

The efficiency may be expressed terms of any two of the following.

$$Compression\ Ratio = r_k = \frac{v_1}{v_2}$$

$$Expansion\ Ratio = r_e = \frac{v_4}{v_3}$$

$$Cut-off\ \ ratio = r_c = \frac{v_3}{v_2}$$

$$r_k = r_e.r_c$$

Process 3-4

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \frac{1}{r_e^{\gamma-1}}$$

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{\gamma-1} = T_3\frac{r_e^{\gamma-1}}{r_k^{\gamma-1}}$$

Process 2-3

$$\frac{T_2}{T_3} = \frac{p_2 v_2}{p_3 v_3} = \frac{v_2}{v_3} = \frac{1}{r_e}$$

$$T_2 = T_3\frac{1}{r_e}$$

Process 1-2

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \frac{1}{r_k^{\gamma-1}}$$

$$T_1 = T_2 \frac{1}{r_k^{\gamma-1}} = \frac{T_3}{r_c}\frac{1}{r_k^{\gamma-1}}$$

By subsisting T1,T2 and T4 in the expression of efficiency

$$\eta = 1 - \frac{T_3 \frac{r_c^{\gamma-1}}{r_k^{\gamma-1}} - \frac{T_3}{r_c}\frac{1}{r_k^{\gamma-1}}}{\gamma\left(T_3 - T_3\frac{1}{r_c}\right)}$$

$$\eta_{diesel} = 1 - \frac{1}{\gamma}\frac{1}{r_c^{\gamma-1}}.\frac{r_c^{\gamma-1}}{r_c - 1}$$

- **Dual Cycle (mixed cycle/ limited pressure cycle):**

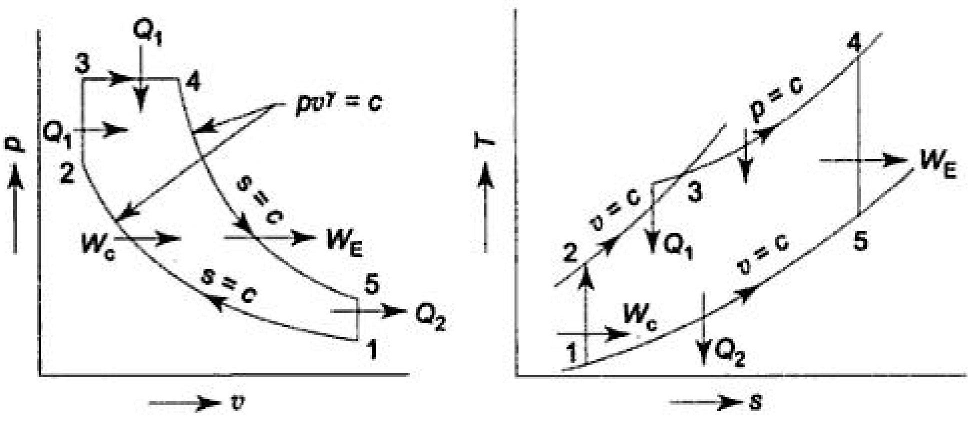
Process 1 → 2 Isentropic compression

Process 2 → 3Constant volume heat addition

Process 3 → 4 Constant pressure heat addition

Process 4 → 5 Isentropic expansion

Process 5→ 1 Constant volume heat rejection



(a) (b)

Thermal Efficiency:

$$\text{where } r_c = {}^{v_3}\!\big/_{v_{2.5}} \text{ and} \sim = {}^{P_3}\!\big/_{P_2}$$

Note, the Otto cycle (r_c=1) and the Diesel cycle (a=1) are special cases:

$$\text{¦}_{Otto} = 1 - \frac{1}{r^{k-1}} \qquad \text{¦}_{\substack{Diesel \\ const\ c_V}} = 1 - \frac{1}{r^{k-1}}\left[\frac{1}{k}\cdot\frac{\left(r_c^k - 1\right)}{\left(r_c - 1\right)}\right]$$

The use of the Dual cycle requires information about either:

i) The fractions of constant volume and constant pressure heat addition (common assumption is to equally split the heat addition), or

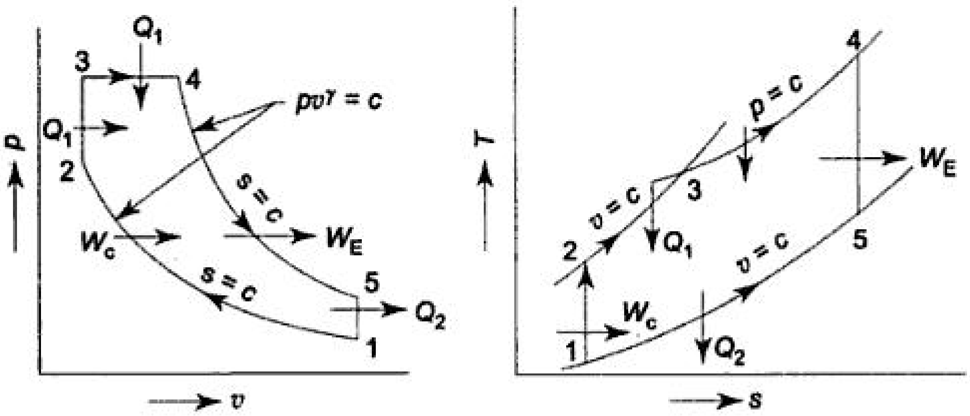
ii) Maximum pressure P_3.

$$Q_1 = mc_v(T_3 - T_2) + mc_p\left(T_4 - T_3\right)$$
$$Q2 = mc_v(T_5 - T_1)$$

Here Q_1 -= heat input

Q_2 =Out put

$$\text{¦} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_5 - T_1)}{mc_v(T_3 - T_2) + mc_p\left(T_4 - T_3\right)} = 1 - \frac{T_5 - T_1}{(T_3 - T_2) + \text{¥}\left(T_4 - T_3\right)}$$



$$Compression\ Ratio = r_k = \frac{v_1}{v_2}$$

$$Expansion\ Ratio = r_e = \frac{v_4}{v_3}$$

$$cons\tan t - volume - pressure - ratio = r_p = \frac{p_3}{p_2}$$

$$r_k = r_c . r_e$$

$$r_e = \frac{r_k}{r_e}$$

$$process 3-4$$

$$r_c = \frac{v_4}{v_3} = \frac{T_4 p_3}{p_4 T_3} = \frac{T_4}{T_3}$$

$$T_3 = \frac{T_4}{r_c}$$

$$\Pr ocess 2-3$$

$$\frac{p_2 v_2}{T_2} = \frac{p_3 v_3}{T_3}$$

$$T_2 = T_3 \frac{p_2}{p_3} = \frac{T_4}{r_p r_c}$$

$$process - 1 - 2$$

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\text{¥}-1} = \frac{1}{r_k^{\text{¥}-1}}$$

$$T_1 = \frac{T_4}{r_p . r_c . r_k^{\text{¥}-1}}$$

Process 4-5

$$T_1 = \frac{T_4}{r_p . r_c . r_k^{\text{¥}-1}}$$

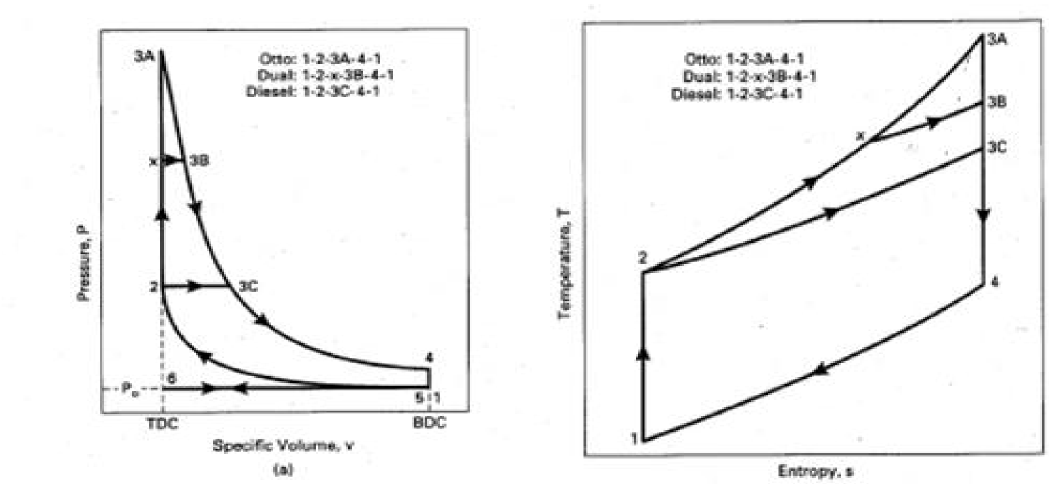
$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{\text{¥}-1} = \frac{1}{r_e^{\text{¥}-1}}$$

$$T_5 = T_4 \frac{r_c^{\text{¥}-1}}{r_k^{\text{¥}-1}}$$

SubtitlingT1, T2,T3 and T4values

$$\eta_{dual} = 1 - \frac{T_4 \dfrac{r_c^{\gamma-1}}{r_k^{\gamma-1}} - \dfrac{T_4}{r_p . r_c . r_k^{\gamma-1}}}{\left(\dfrac{T_4}{r_c} - \dfrac{T_4}{r_p r_c}\right) + \gamma \left(T_4 - \dfrac{T_4}{r_c}\right)} = 1 - \frac{1}{r_k^{\gamma-1}} \frac{r_p r_c^{\gamma-1}}{r_p - 1 + \gamma r_p \left(r_c - 1\right)}$$

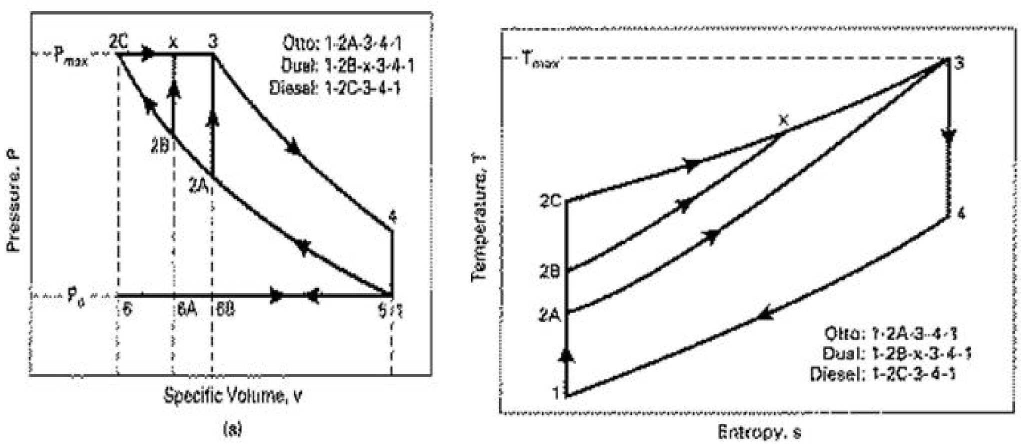
- **Comparison of cycles:**
  - For the same inlet conditions P_1, V_1 and the same compression ratio P_2/P_1:



For the same initial conditions P_1, V_1 and the same compression ratio:

$$\eta_{Otto} > \eta_{Dual} > \eta_{Diesel}$$

  - For the same inlet conditions P_1, V_1 and the same peak pressure P_3:



For the same initial conditions P_1, V_1 and the same peak pressure P_3

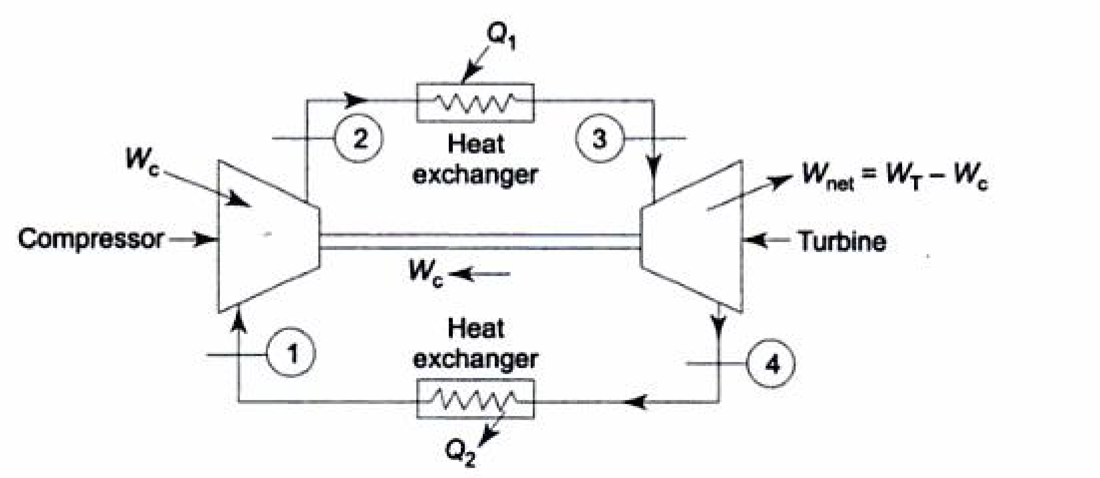
(Actual design limitation in engines):

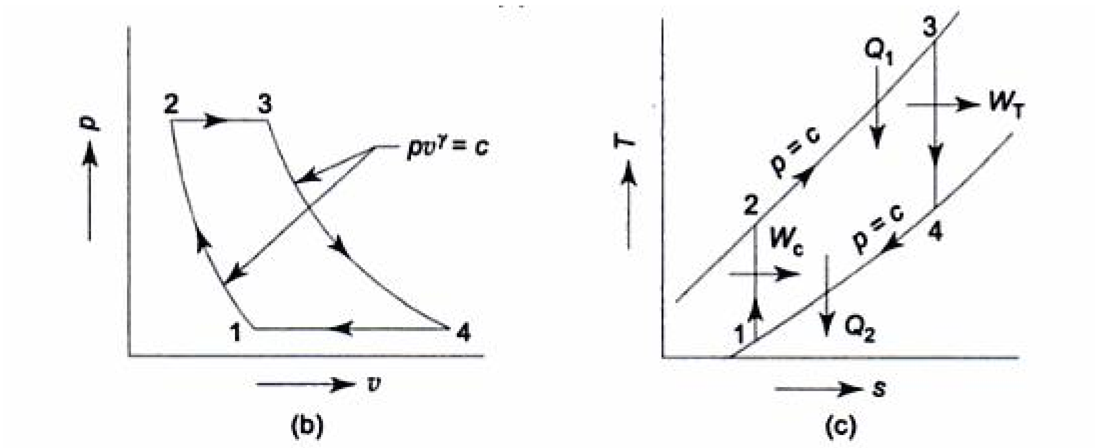
$$\eta_{Diesel} > \eta_{Dual} > \eta_{otto}$$

- **Brayton Cycle (or Joule cycle)**

The Brayton cycle is the air-standard ideal cycle approximation for the gas-turbine engine. This cycle differs from the Otto and Diesel cycles in that the processes making the cycle occur in open systems or control volumes. Therefore, an open system, steady-flow analysis is used to determine the heat transfer and work for the cycle.

We assume the working fluid is air and the specific heats are constant and will consider the cold-air-standard cycle.





The closed cycle gas-turbine engine

The *T-s* and *P-v* diagrams for the

Closed Brayton Cycle

Process	Description
1-2	Isentropic compression (in a compressor)
2-3	Constant pressure heat addition
3-4	Isentropic expansion (in a turbine)
4-1	Constant pressure heat rejection

Thermal efficiency of the Brayton cycle

$$\eta_{th,\,Brayton} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Now to find Q_{in} and Q_{out}.

Apply the conservation of energy to process 2-3 for P = constant (no work), steady-flow, and neglect changes in kinetic and potential energies.

$$\dot{E}_{in} = \dot{E}_{out}$$
$$\dot{m}_2 h_2 + \dot{Q}_{in} = \dot{m}_3 h_3$$

The conservation of mass gives

$$\dot{m}_{in} = \dot{m}_{out}$$
$$\dot{m}_2 = \dot{m}_3 = \dot{m}$$

For constant specific heats, the heat added per unit mass flow is

$$\dot{Q}_{in} = \dot{m}(h_3 - h_2)$$
$$\dot{Q}_{in} = \dot{m}C_p(T_3 - T_2)$$
$$q_{in} = \frac{\dot{Q}_{in}}{\dot{m}} = C_p(T_3 - T_2)$$

The conservation of energy for process 4-1 yields for constant specific heats

$$\dot{Q}_{out} = \dot{m}(h_4 - h_1)$$
$$\dot{Q}_{out} = \dot{m}C_p(T_4 - T_1)$$
$$q_{out} = \frac{\dot{Q}_{out}}{\dot{m}} = C_p(T_4 - T_1)$$

The thermal efficiency becomes

$$\eta_{th,\,Brayton} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$= 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$$

$$\boxed{\eta_{th,\,Brayton} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}}$$

$$= 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}}$$

Since $P_3 = P_2$ and $P_4 = P_1$,

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

or

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

The Brayton cycle efficiency becomes

$$\eta_{th,\,Brayton} = 1 - \frac{T_1}{T_2}$$

Since process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = r_p^{\frac{\gamma-1}{\gamma}}$$

$$\frac{T_1}{T_2} = \frac{1}{r_p^{\frac{(\gamma-1)}{\gamma}}}$$

Where the pressure ratio is $r_p = P_2/P_1$ and

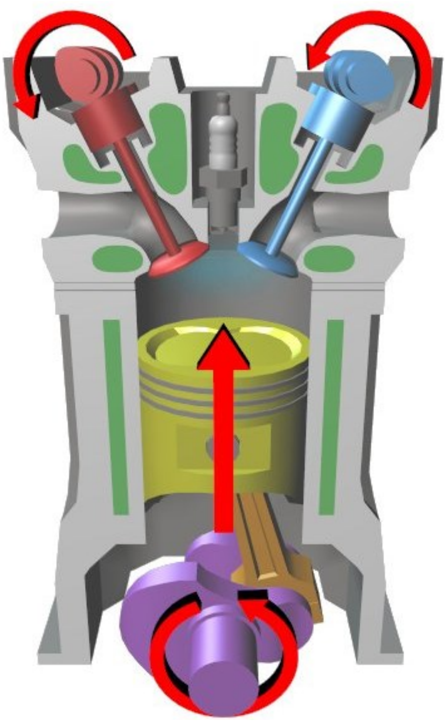
$$\boxed{\eta_{th,\,Brayton} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}}$$

UNIT 1

ACTUAL CYCLES & ANALYSIS

1

Introduction



Course Contents

1.1 Introduction

1.2 Basic components and terminology of IC engine

1.3 Working of 4-Stroke SI engine

1.4 Working of 4-Stroke CI engine

1.5 Comparison of SI and CI Engines

1.6 Two-Stroke Engine

1.7 IC Engine classification

1.8 Application of IC Engine

1.9 Engine Performance Parameters

1.10 Air standard cycles

1.1 Introduction

- Once man discovered the use of heat in the form of fire, it was just a step to formulate the energy interactions. With this, human beings started to use heat energy for cooking, warming up living spaces, drying and so on.
- Further, due to the development of civilization and increase in population, man had to move from one place to another. Animals were used in transportation between the 4^{th} and 5^{th} centuries BC, and spread to Europe and other countries in the 5^{th} century BC and China in about 1200 BC.
- Gradually, man replaced the animals with motive power that was used in transportation. The use of power vehicles began in the late 18th century, with the creation of the steam engine. The invention of Otto (1876) and Diesel (1892) cycles in the 19th century transformed the method of propulsion from steam to petroleum fuel.
- **ENGINE:** Engine is a device which converts one form of Energy into another form
- **HEAT ENGINE:** Heat engine is a device which transforms the chemical energy of a fuel into thermal energy and utilizes this thermal energy to perform useful work. Thus, thermal energy is converted to mechanical energy in a heat engine.
- Heat engines can be broadly classified into two categories:
  a) Internal Combustion Engines (IC Engines)
  b) External Combustion Engines (EC Engines)

1.1.1 Classification of heat engines

- Engines whether Internal Combustion or External Combustion are of two types:
  (i) Rotary engines
  (ii) Reciprocating engines
- A detailed classification of heat engines is given in Fig. 1.1.

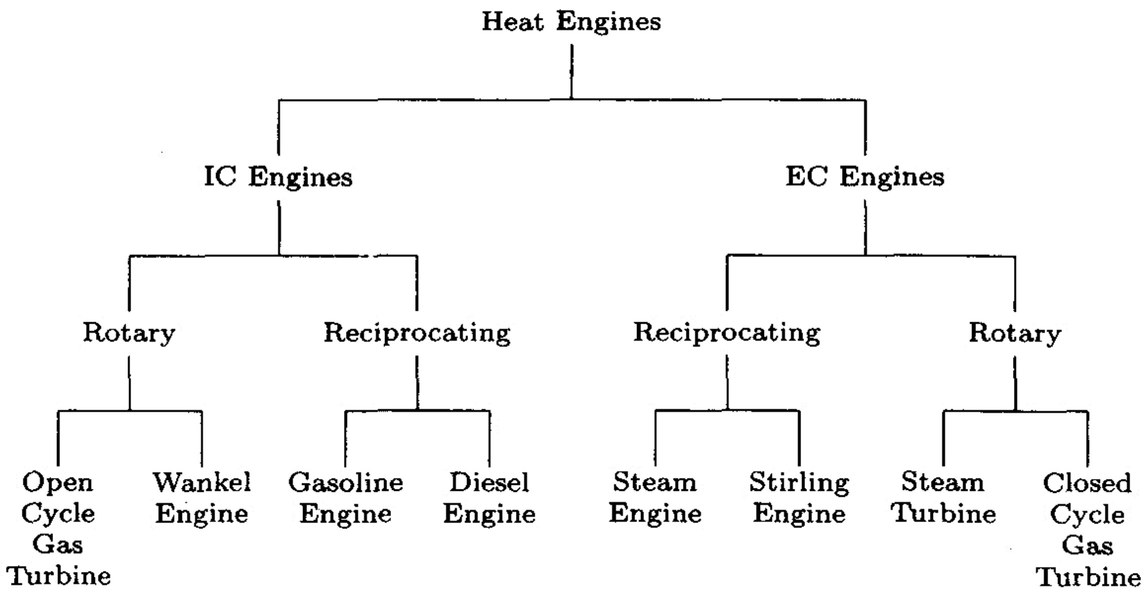


Fig 1.1 Classification of heat engines

1.1.2 Comparison of I.C. Engines and E.C. Engines

- Comparison of IC engine and EC engine is given in table 1.1.

Table 1.1 Comparison of IC engine and EC engine

I.C. Engine	E.C. engine
1. Combustion of fuel takes place inside the cylinder	1. Combustion of fuel takes place outside the cylinder
2. Working fluid may be Petrol, Diesel & Various types of gases	2. Working fluid is steam
3. Require less space	3. Require large space
4. Capital cost is relatively low	4. Capital cost is relatively high
5. Starting of this engine is easy & quick	5. Starting of this engine requires time
6. Thermal efficiency is high	6. Thermal Efficiency is low
7. Power developed per unit weight of these engines is high	7. Power Developed per unit weight of these engines is low
8. Fuel cost is relatively high	8. Fuel cost is relatively low

1.2 Basic components and terminology of IC engines

- Even though reciprocating internal combustion engines look quite simple, they are highly complex machines. There are many components which have to perform their functions effectively to produce output power.
- There are two types of engines, viz., spark-ignition (SI) and compression-ignition (Cl) engine.

1.2.1 Engine Components

- A cross section of a single cylinder spark-ignition engine with overhead valves is shown in Fig.1.2. The major components of the engine and their functions are briefly described below.

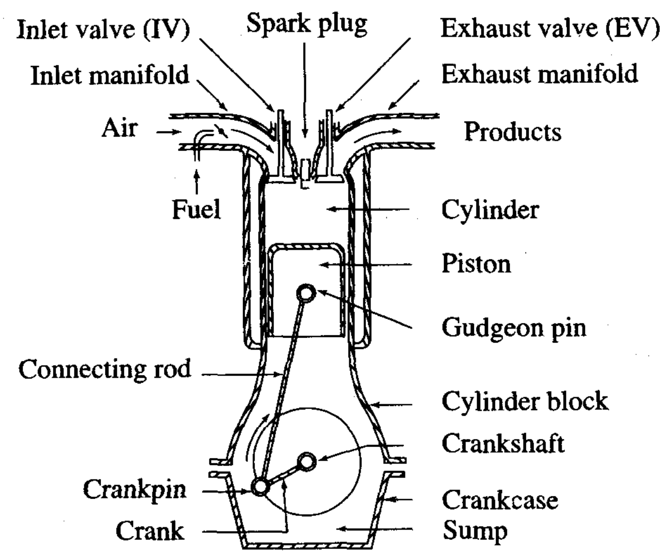


Fig. 1.2 Cross-section of spark-ignition engine

a) Cylinder block

- The cylinder block is the main supporting structure for the various components. The cylinder of a multicylinder engine are cast as a single unit, called cylinder block. The cylinder head is mounted on the cylinder block. The cylinder head and cylinder block are provided with water jackets in the case of water cooling or with cooling fins in the case of air cooling.

b) Cylinder

- As the name implies it is a cylindrical vessel or space in which the piston makes a reciprocating motion. The varying volume created in the cylinder during the operation of the engine is filled with the working fluid and subjected to different thermodynamic processes. The cylinder is supported in the cylinder block.

c) Piston

- It is a cylindrical component fitted into the cylinder forming the moving boundary of the combustion system. It fits perfectly (snugly) into the cylinder providing a gas-tight space with the piston rings and the lubricant. It forms the first link in transmitting the gas forces to the output shaft.

d) Combustion chamber

- The space enclosed in the upper part of the cylin-der, by the cylinder head and the piston top during the combustion process, is called the combustion chamber. The combustion of fuel and the consequent release of thermal energy results in the building up of pressure in this part of the cylinder.

e) Inlet manifold

- The pipe which connects the intake system to the inlet valve of the engine and through which air or air-fuel mixture is drawn into the cylinder is called the inlet manifold.

f) Exhaust manifold

- The pipe which connects the exhaust system to the exhaust valve of the engine and through which the products of combustion escape into the atmosphere is called the exhaust manifold.

g) Inlet and Exhaust valves

- Valves are commonly mushroom shaped pop-pet type. They are provided either on the cylinder head or on the side of the cylinder for regulating the charge coming into the cylinder (inlet valve) and for discharging the products of combustion (exhaust valve) from the cylinder.

h) Spark Plug

- It is a component to initiate the combustion process in Spark- Ignition (SI) engines and is usually located on the cylinder head.

i) Connecting Rod

- It interconnects the piston and the crankshaft and trans-mits the gas forces from the piston to the crankshaft. The two ends of the connecting rod are called as small end and the big end (Fig.1.3). Small end is connected to the piston by gudgeon pin and the big end is connected to the crankshaft by crankpin.

j) Crankshaft

- It converts the reciprocating motion of the piston into useful rotary motion of the output shaft. In the crankshaft of a single cylinder engine there are a pair of crank arms and balance weights. The balance weights are provided for static and dynamic balancing of the rotating system. The crankshaft is enclosed in a crankcase.

k) Piston rings

- Piston rings, fitted into the slots around the piston, provide a tight seal between the piston and the cylinder wall thus preventing leakage of combustion gases.

l) Gudgeon pin

- It links the small end of the connecting rod and the piston.

m) Camshaft

- The camshaft (not shown in the figure) and its associated parts control the opening and closing of the two valves. The associated parts are push rods, rocker arms, valve springs and tappets. This shaft also provides the drive to the ignition system. The camshaft is driven by the crankshaft through timing gears.

n) Cams

- These are made as integral parts of the camshaft and are so de-signed to open the valves at the correct timing and to keep them open for the necessary duration.

o) Flywheel

- The net torque imparted to the crankshaft during one complete cycle of operation of the engine fluctuates causing a change in the angular velocity of the shaft. In order to achieve a uniform torque an inertia mass in the form of a wheel is attached to the output shaft and this wheel is called the flywheel.

p) Carburetor

- Carburetor is used in petrol engine for proper mixing of air and petrol.

q) Fuel pump

- Fuel pump is used in diesel engine for increasing pressure and controlling the quantity of fuel supplied to the injector.

r) Fuel injector

- Fuel injector is used to inject diesel fuel in the form of fine atomized spray under pressure at the end of compression stroke.

1.2.2 Terminologies used in IC engine

- **Cylinder Bore (d):** The nominal inner diameter of the working cylinder is called the cylinder bore and is designated by the letter d and is usually expressed in millimeter (mm).
- **Piston Area (A):** The area of a circle of diameter equal to the cylinder bore is called the piston area and is designated by the letter A and is usually expressed in square centimeter (cm^2).
- **Stroke (L):** It is the linear distance traveled by the piston when it moves from one end of the cylinder to the other end. It is equal to twice the radius of the crank. It is designated by the letter L and is expressed usually in millimeter (mm).

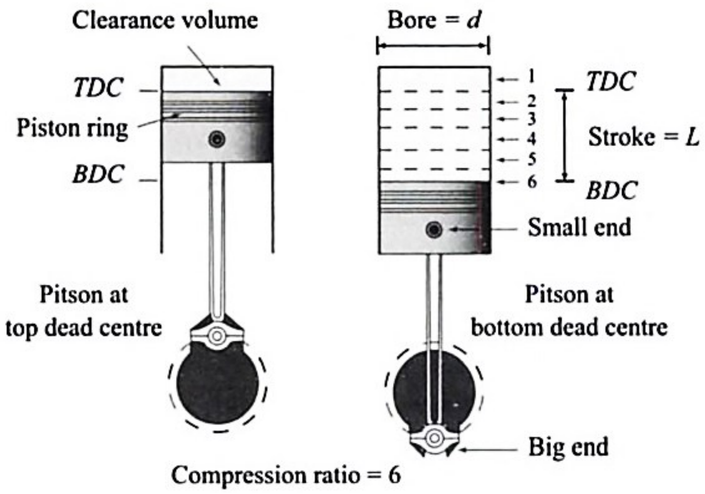


Fig 1.3 IC Engine nomenclature

- **Stroke to Bore Ratio (L/d):** L / d ratio is an important parameter in classifying the size of the engine.
    - If d < L, it is called under-square engine.
    - If d = L, it is called square engine.
    - If d > L, it is called over-square engine.

  An over-square engine can operate at higher speeds because of larger bore and shorter stroke.
- **Dead Centre:**
  In the vertical engines, top most position of the piston is called Top Dead Centre (TDC). When the piston is at bottom most position, it is called Bottom Dead Centre (BDC).
  In horizontal engine, the extreme position of the piston near to cylinder head is called Inner Dead Centre (IDC.) and the extreme position of the piston near the crank is called Outer Dead Centre (O.D.C.).
- **Displacement or Swept Volume (V_s)**: The volume displaced by the piston in one stroke is known as stroke volume or swept volume. It is expressed in terms of cubic centimeter (cc) and given by

$$V_s = A \times L = \frac{\pi}{4} d^2 L$$

- **Cubic Capacity or Engine Capacity:** The displacement volume of a cylinder multiplied by number of cylinders in an engine will give the cubic capacity or the engine capacity. For example, if there are K cylinders in an engine, then

$$\text{Cubic capacity} = V_s \times K$$

- **Clearance Volume (V_c):** It is the volume contained between the piston top and cylinder head when the piston is at top or inner dead center.
- **Compression Ratio (r):** The ratio of total cylinder volume to clearance volume is called the compression ratio (r) of the engine.

$$r = \frac{Total\ cylinder\ volume}{Clearance\ volume}$$

$$\therefore r = \frac{V_c + V_s}{V_c}$$

For petrol engine r varies from 6 to 10 and for Diesel engine r varies from 14 to 20.

- **Piston speed (V_p):** It is average speed of piston. It is equal to 2LN, where N is speed of crank shaft in rev/sec.

$$V_p = \frac{2LN}{60}\ {}^{m}/_{sec}$$

where, L = Stroke length, m

N = Speed of crank shaft, RPM

1.3 Working of Four Stroke Spark-Ignition Engine

- In a four-stroke engine, the cycle of operations is completed in four strokes of the piston or two revolutions of the crankshaft.
- During the four strokes, there are five events to be completed, viz., suction, compression, combustion, expansion and exhaust. Each stroke consists of 180° of crankshaft rotation and hence a four-stroke cycle is completed through 720° of crank rotation.
- The cycle of operation for an ideal four-stroke SI engine consists of the following four strokes: (i) suction or intake stroke; (ii) compression stroke; (iii) expansion or power stroke and (iv) exhaust stroke.

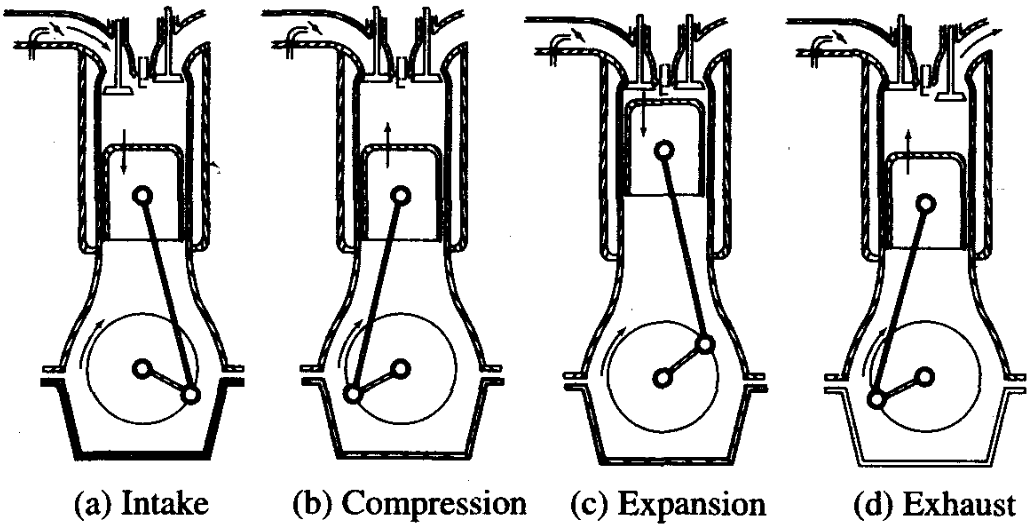


Fig. 1.4 Working principle of a four-stroke SI engine

- The details of various processes of a four-stroke spark-ignition engine with overhead valves are shown in Fig. 1.4 (a-d). When the engine completes all the five events under ideal cycle mode, the pressure-volume (p-V) diagram will be as shown in Fig.1.5.

a) **Suction or Intake Stroke:** Suction stroke 0→1 (Fig.1.5) starts when the piston is at the top dead centre and about to move downwards. The inlet valve is assumed to open instantaneously and at this time the exhaust valve is in the closed position, Fig.1.4 (a).

- Due to the suction created by the motion of the piston towards the bottom dead centre, the charge consisting of fuel-air mixture is drawn into the cylinder. When the piston reaches the bottom dead centre the suction stroke ends and the inlet valve closes instantaneously.

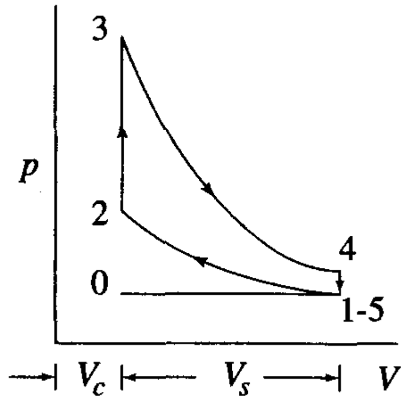


Fig. 1.5 Ideal p-V diagram of a four-stroke SI engine

b) **Compression Stroke:** The charge taken into the cylinder during the suction stroke is compressed by the return stroke of the piston 1→2, (Fig.1.5). During this stroke both inlet and exhaust valves are in closed position, Fig. 1.4(b).

- The mixture which fills the entire cylinder volume is now compressed into the clearance volume. At the end of the compression stroke the mixture is ignited with the help of a spark plug located on the cylinder head.
- In ideal engines it is assumed that burning takes place instantaneously when the piston is at the top dead centre and hence the burning process can be approximated as heat addition at constant volume.
- During the burning process the chemical energy of the fuel is converted into heat energy producing a temperature rise of about 2000 °C (process 2→3), Fig.1.5. The pressure at the end of the combustion process is considerably increased due to the heat release from the fuel.

c) **Expansion or Power Stroke:** The high pressure of the burnt gases forces the piston towards the BDC, (stroke 3→4) Fig .1.5. Both the valves are in closed position, Fig. 1.4(c). Of the four-strokes only during this stroke power is produced. Both pressure and temperature decrease during expansion.

d) **Exhaust Stroke:** At the end of the expansion stroke the exhaust valve opens instantaneously and the inlet valve remains closed, Fig. 1.4(d). The pressure falls to atmospheric level a part of the burnt gases escape. The piston starts moving from the bottom dead centre to top dead centre (stroke 5→0), Fig.1.5 and sweeps the burnt gases out from the cylinder almost at atmospheric pressure. The exhaust valve closes when the piston reaches TDC.

- At the end of the exhaust stroke and some residual gases trapped in the clearance volume remain in the cylinder. These residual gases mix with the fresh charge coming in during the following cycle, forming its working fluid.

- Each cylinder of a four-stroke engine completes the above four operations in two engine revolutions, first revolution of the crankshaft occurs during the suction and compression strokes and the second revolution during the power and exhaust strokes.
- Thus for one complete cycle there is only one power stroke while the crankshaft makes two revolutions. For getting higher output from the engine the heat addition (process 2→3) should be as high as possible and the heat rejection (process 3→4) should be as small as possible. Hence, one should be careful in drawing the ideal p - V diagram (Fig.1.5), which should represent the processes correctly.

1.4 Working of Four Stroke Compression-Ignition Engine

- The four-stroke CI engine is similar to the four-stroke SI engine but it operates at a much higher compression ratio. The compression ratio of an SI engine is between 6 and 10 while for a CI engine it is from 16 to 20.
- In the CI engine during suction stroke, air, instead of a fuel-air mixture, is inducted. Due to higher compression ratios employed, the temperature at the end of the compression stroke is sufficiently high to self-ignite the fuel which is injected into the combustion chamber.
- In CI engines, a high pressure fuel pump and an injector are provided to inject the fuel into the combustion chamber. The carburetor and ignition system necessary in the SI engine are not required in the CI engine.
- The ideal sequence of operations for the four-stroke CI engine as shown in Fig. 1.6 is as follows:

a) **Suction Stroke:** In the suction stroke piston moves from TDC to BDC. Air alone is inducted during the suction stroke. During this stroke inlet valve is open and exhaust valve is closed, Fig.1.6 (a).

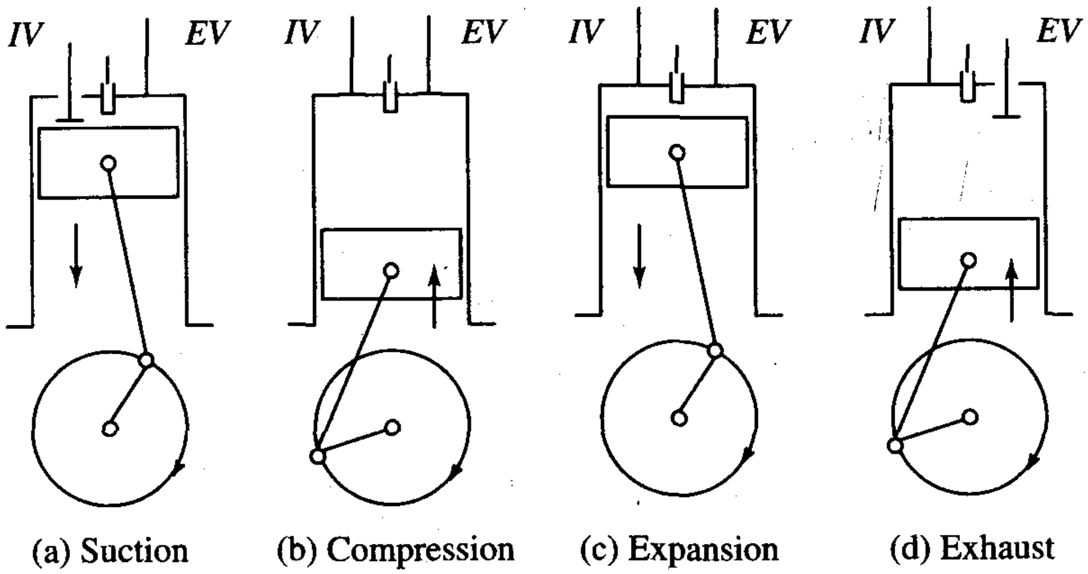


Fig. 1.6 Cycle of operation of CI engine

b) **Compression Stroke:** In this stroke piston moves from BDC to TDC. Air inducted during the suction stroke is compressed into the clearance volume. Both valves remain closed during this stroke, Fig. 1.6 (b).

c) **Expansion Stroke:** Fuel injection starts nearly at the end of the com-pression stroke. The rate of injection is such that combustion maintains the pressure constant in spite of the piston movement on its expansion stroke increasing the volume. Heat is assumed to have been added at constant pressure. After the injection of fuel is completed (i.e. after cut-off) the products of combustion expand. Both the valves remain closed during the expansion stroke, Fig. 1.6(c).

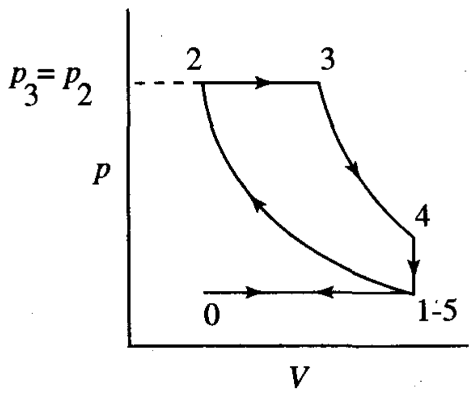


Fig. 1.7 Ideal p-V diagram for a four stroke CI engine

d) **Exhaust Stroke:** The piston travelling from BDC to TDC pushes out the products of combustion. The exhaust valve is open and the intake valve is closed during this stroke, Fig. 1.6 (d). The ideal p - V diagram is shown in Fig. 1.7.

- Due to higher pressures in the cycle of operations the CI engine has to be sturdier than a SI engine for the same output. This results in a CI engine being heavier than the SI engine. However, it has a higher thermal efficiency on account of the high compression ratio (of about 18 as against about 8 in SI engines) used.

1.5 Comparison of SI and CI Engines

- The detailed comparison of SI and CI engine is given in table 1.2

Table 1.2 Comparison of SI and CI Engines

Description	SI Engine	CI Engine
Basic cycle	Works on Otto cycle or constant volume heat addition cycle.	Works on Diesel cycle or constant pressure heat addition cycle.
Fuel	Gasoline, a highly volatile fuel. Self-ignition temperature is high.	Diesel oil, a non-volatile fuel. Self-ignition temperature is comparatively low
Introduction of fuel	A gaseous mixture of fuel-air is introduced during the suction stroke. A carburetor and an ignition system are necessary. Modern engines have gasoline injection.	Fuel is injected directly into the combustion chamber at high pressure at the end of the compression stroke. A fuel pump and injector are necessary.
Load control	Throttle controls the quantity of fuel-air mixture to control the load.	The quantity of fuel is regulated to control the load. Air quantity is not controlled.

Ignition	Requires an ignition system with spark plug in the combustion chamber. Primary voltage is provided by either a battery or a magneto.	Self-ignition occurs d u e to high temperature of air because of the high compression. Ignition system and spark plug are not necessary.
Compression ratio	6 to 10. Upper limit is fixed by anti- knock quality of the fuel.	16 to 20. Upper limit is limited by weight increase of the engine.
Speed	Due to light weight and also due to homogeneous combustion, they are high speed engines.	Due to heavy weight and also due to heterogeneous combustion, they are low speed engines.
Thermal efficiency	Because of the lower CR, the maximum value of thermal efficiency that can be obtained is lower.	Because of higher CR, the maximum value of thermal efficiency that can be obtained is higher.
Weight	Lighter due to comparatively lower peak pressures.	Heavier due to comparatively higher peak pressures.

1.6 Two-Stroke Engine

- In two-stroke engines the cycle is completed in one revolution of the crankshaft. The main difference between two-stroke and four-stroke engines is in the method of filling the fresh charge and removing the burnt gases from the cylinder.
- In the four-stroke engine these operations are performed by the engine piston during the suction and exhaust strokes respectively.
- In a two- stroke engine, the filling process is accomplished by the charge compressed in crankcase or by a blower. The induction of the compressed charge moves out the product of combustion through exhaust ports. Therefore, no separate piston strokes are required for these two operations.
- Two strokes are sufficient to complete the cycle, one for compressing the fresh charge and the other for expansion or power stroke. It is to be noted that the effective stroke is reduced.
- Figure 1.8 shows one of the simplest two-stroke engines, viz., the crankcase scavenged engine. Figure 1.9 shows the ideal p - V diagram of such an engine.
- The air-fuel charge is inducted into the crankcase through the spring loaded inlet valve when the pressure in the crankcase is reduced due to upward motion of the piston during compression stroke. After the compression and ignition, expansion takes place in the usual way.
- During the expansion stroke the charge in the crankcase is compressed. Near the end of the expansion stroke, the piston uncovers the exhaust ports and the cylinder pressure drops to atmospheric pressure as the combustion products leave the cylinder.
- Further movement of the piston uncovers the transfer ports, permitting the slightly compressed charge in the crankcase to enter the engine cylinder.

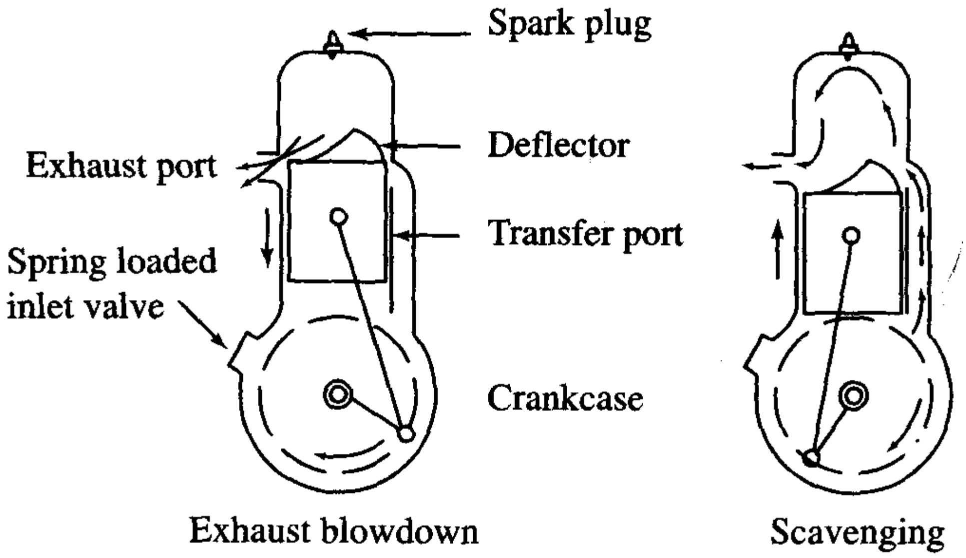


Fig. 1.8 Crankcase scavenged two-stroke SI engine

- The piston top usually has a projection to deflect the fresh charge towards the top of the cylinder preventing the flow through the exhaust ports. This serves the double purpose of scavenging the combustion products from the upper part of the cylinder and preventing the fresh charge from flowing out directly through the exhaust ports.
- The same objective can be achieved without piston deflector by proper shaping of the transfer port. During the upward motion of the piston from B D C the transfer ports close first and then the exhaust ports, thereby the effective compression of the charge begins and the cycle is repeated.

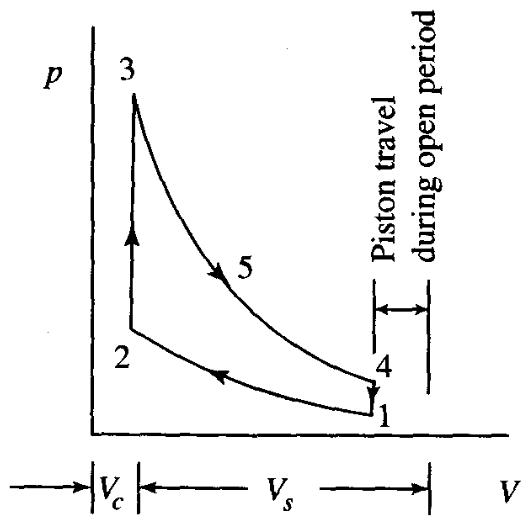


Fig 1.9 Ideal p-V diagram of a two-stroke SI engine

1.7 IC engine Classification

- I.C. Engines may be classified according to,
  a) Type of the fuel used as :
     (1) Petrol engine (2) Diesel engine
     (3) Gas engine (4) Bi-fuel engine (Two fuel engine)
  b) Nature of thermodynamic cycle as :
     (1) Otto cycle engine (2) Diesel cycle engine
     (3) Duel or mixed cycle engine
  c) Number of strokes per cycle as :
     (1) Four stroke engine (2) Two stroke engine

d) Method of ignition as :

(1) Spark ignition engine (S.I. engine)

Mixture of air and fuel is ignited by electric spark.

(2) Compression ignition engine (C.I. engine)

The fuel is ignited as it comes in contact with hot compressed air.

e) Method of cooling as :

(1) Air cooled engine (2) Water cooled engine

f) Speed of the engine as :

(1) Low speed (2) Medium speed

(3) High speed

Petrol engine are high speed engines and diesel engines are low to medium speed engines

g) Number of cylinder as :

(1) Single cylinder engine (2) Multi cylinder engine

h) Position of the cylinder as :

(1) Inline engines (2) V – engines

(3) Radial engines (4) Opposed cylinder engine

(5) X – Type engine (6) H – Type Engine

(7)U – Type Engine (8) Opposed piston engine

(9) Delta Type Engine

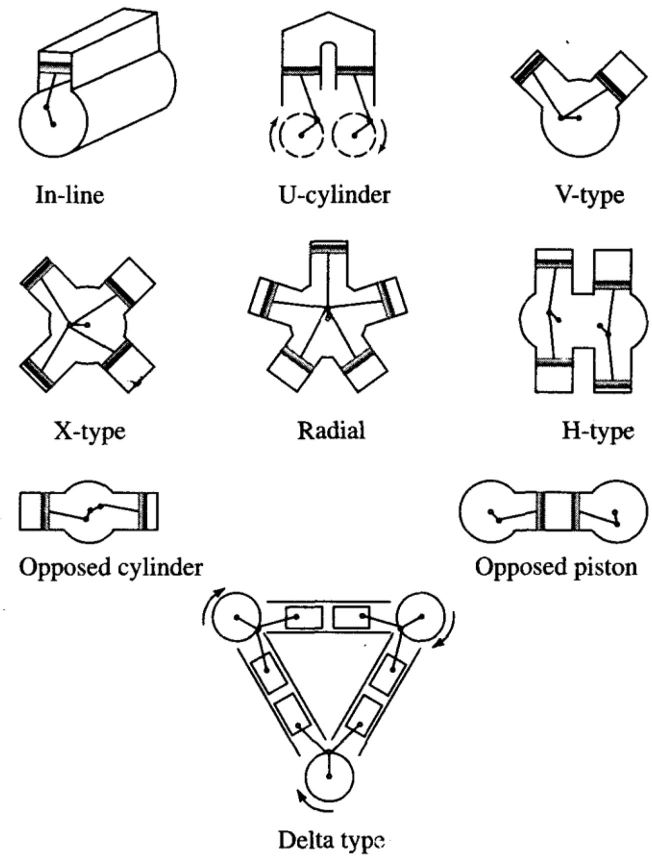


Fig. 1.10 Engine classification by cylinder arrangements

1.8 Application of IC Engines

- The most important application of IC engines is in transport on land, sea and air. Other applications include industrial power plants and as prime movers for electric generators. Table 1.3 gives, in a nutshell, the applications of both IC and EC engines.

Table 1.3 Application of Engines

IC Engine		EC Engine	
Type	Application	Type	Application
Gasoline engines	Automotive, Marine, Aircraft	Steam Engines	Locomotives, Marine
Gas engines	Industrial power	Stirling Engines	Experimental Space Vehicles
Diesel engines	Automotive, Railways, Power, Marine	Steam Turbines	Power, Large Marine
Gas turbines	Power, Aircraft, Industrial, Marine	Close Cycle Gas Turbine	Power, Marine

1.9 Engine Performance Parameters

- The engine performance is indicated by the term efficiency, η. Five important engine efficiencies and other related engine performance parameters are discussed below.

1.9.1 Indicated Power

- The power produced inside the engine cylinder by burning of fuel is known as Indicated power (I.P.) of engine. It is calculated by finding the actual mean effective pressure.

$$Actual\ mean\ effective\ pressure,\ P_m = \frac{sa}{l}\ N/m^2 \quad (1.1)$$

where,
a = Area of the actual indicator diagram, cm^2
l = Base width of the indicator diagram, cm
s = Spring value of the spring used in the indicator, $N/m^2/cm$

$$ip = \frac{P_m L A n}{60000}\ kW \quad (1.2)$$

where,
P_m = Mean effective pressure N/m^2
L = Length of stroke, m
A = Area of cross section of the cylinder, m^2
N = RPM of the engine crank shaft

$n = \frac{N}{2}$ for 4-stroke

$n = N$ for 2-stroke

1.9.2 Brake power

- It is the power available at engine crank shaft for doing useful work. It is also known as engine output power. It is measured by dynamometer.

$$B.P. = \frac{2\pi NT}{60000} = \frac{P_{mb}LAn}{60000}\ kW \tag{1.3}$$

where

$$T = W \times R \tag{1.4}$$

W = Net load acting on the brake drum, N

R = Effective radius of the brake drum, m

N = RPM of the crank shaft

T = Resisting torque, Nm

P_{mb} = Brake mean effective pressure

1.9.3 Indicated Thermal Efficiency (η_{ith})

- Indicated thermal efficiency is the ratio of energy in the indicated power, ip, to the input fuel energy in appropriate units.

$$\eta_{ith} = \frac{ip\ [kJ/s]}{\text{energy in fuel per second } [kJ/s]} \tag{1.1}$$

$$\eta_{ith} = \frac{ip}{\text{mass of fuel/s} \times \text{CV of fuel}} = \frac{ip}{m_f \times CV} \tag{1.2}$$

1.9.4 Brake Thermal Efficiency (η_{bth})

- Brake thermal efficiency is the ratio of power available at crank shaft, bp, to the input fuel energy in appropriate units.

$$\eta_{bth} = \frac{bp}{\text{mass of fuel/s} \times \text{CV of fuel}} = \frac{bp}{m_f \times CV} \tag{1.3}$$

1.9.5 Mechanical Efficiency (η_m)

- Mechanical efficiency is defined as the ratio of brake power (delivered power) to the indicated power (power provided to the piston).

$$\eta_m = \frac{bp}{ip} = \frac{bp}{bp + fp} \tag{1.4}$$

$$fp = ip - bp \tag{1.5}$$

1.9.6 Volumetric Efficiency (η_v)

- Volumetric efficiency indicates the breathing ability of the engine. It is to be noted that the utilization of the air is that determines the power output of the engine. Intake system must be designed in such a way that the engine must be able to take in as much air as possible.
- Volumetric efficiency is defined as the ratio of actual volume flow rate of air into the intake system to the rate at which the volume is displaced by the system.

$$\eta_v = \frac{\text{Actual volume of charge or air sucked at atm. condition}}{\text{Swept volume}} \tag{1.6}$$

1.9.7 Air standard efficiency

- It is the efficiency of the thermodynamic cycle of the engine.

- For petrol engine,

$$\eta_{air} = 1 - \frac{1}{(r)^{\gamma-1}} \tag{1.7}$$

- For diesel engine,

$$\eta_{air} = 1 - \frac{1}{(r)^{\gamma-1}} \left[\frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)} \right] \tag{1.8}$$

1.9.8 Relative Efficiency or Efficiency Ratio

- Relative efficiency or efficiency ratio is the ratio of thermal efficiency of an actual cycle to that of the ideal cycle. The efficiency ratio is a very useful criterion which indicates the degree of development of the engine.

$$\eta_{rel} = \frac{\eta_{th}}{\eta_{air}} \tag{1.9}$$

1.9.9 Specific output

- The specific output of the engine is defined as the power output per unit area.

$$Specific\,output = \frac{B.P.}{A} \tag{1.10}$$

1.9.10Specific fuel consumption

- Specific fuel consumption (SFC) is defined as the amount of fuel consumed by an engine for one unit of power production. SFC is used to express the fuel efficiency of an I.C. engine.

$$SFC = \frac{m_f}{B.P.}\ \mathrm{k}g/\mathrm{k}Wh \tag{1.11}$$

1.10 Air Standard Cycles

- In most of the power developing systems, such as petrol engine, diesel engine and gas turbine, the common working fluid used is air. These devices take in either a mixture of fuel and air as in petrol engine or air and fuel separately and mix them in the combustion chamber as in diesel engine
- The mass of fuel used compared with the mass of air is rather small. Therefore the properties of mixture can be approximated to the properties of air.
- Exact condition existing within the actual engine cylinder are very difficult to determine, but by making certain simplifying assumptions, it is possible to approximate these conditions more or less closely. The approximate engine cycles thus analysed are known as theoretical cycles.
- The simplest theoretical cycle is called the air-cycle approximation. The air-cycle approximation used for calculating conditions in internal combustion engine is called the air-standard cycle.

– The analysis of all air-standard cycles is based upon the following assumption:

a) The gas in the engine cylinder is a perfect gas, i.e. it obeys the gas laws and has constant specific heats.

b) The physical constants of the gas in the cylinder are the same as those of air at moderate temperatures i.e., the molecular weight of cylinder gas is 29 and C_p = 1.005 kJ/kg K and C_v = 0.718 kJ/kg K.

c) The compression and expansion processes are adiabatic and they take place without internal friction, i.e., these processes are isentropic.

d) No chemical reaction takes place in the cylinder. Heat is supplied or rejected by bringing a hot body or a cold body in contact with cylinder at appropriate points during the process.

e) The cycle is considered closed, with the same 'air' always remaining in the cylinder to repeat the cycle.

– Because of many simplifying assumptions, it is clear that the air-cycle approximation does not closely represent the conditions within the actual cylinder. Due to the simplicity of the air-cycle calculation, it is often used to obtain approximate answers to complex engine problems.

1.10.1 The Otto Cycle *__OR__* Constant Volume Cycle (Isochoric)

– The cycle was successfully applied by a German scientist Nicolous A. Otto to produce a successful 4 – stroke cycle engine in 1876.

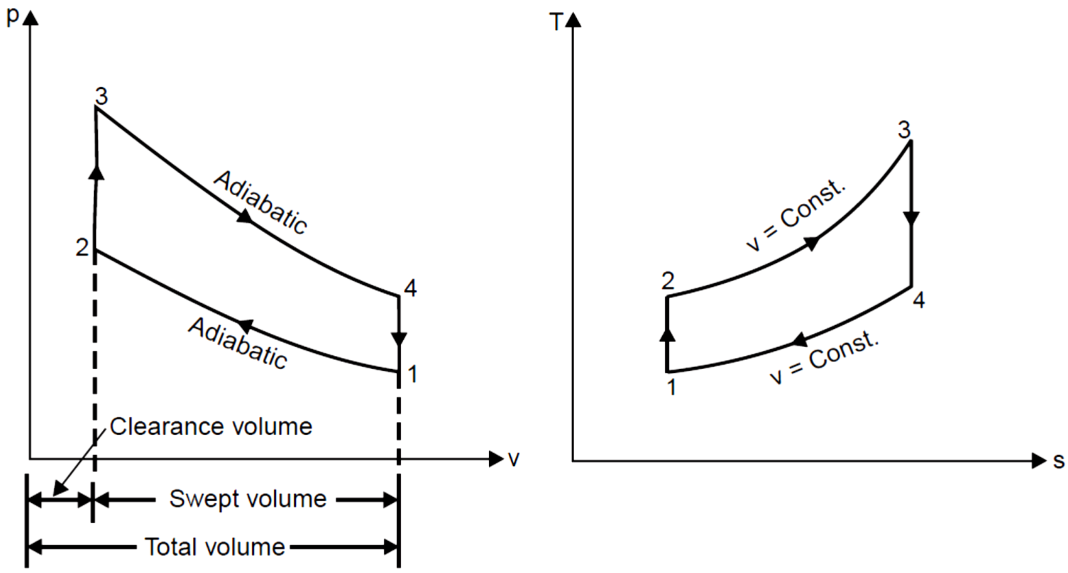


Fig. 1.11 p-V and T-s diagrams of Otto cycle

– The thermodynamic cycle is operated with isochoric (constant volume) heat addition and consists of two adiabatic processes and two constant volume changes.

– Fig. 1.11 shows the Otto cycle plotted on p – V and T – s diagram.

__Adiabatic Compression Process (1 – 2):__

– At pt. 1 cylinder is full of air with volume V_1, pressure P_1 and temp. T_1.

- Piston moves from BDC to TDC and an ideal gas (air) is compressed isentropically to state point 2 through compression ratio,

$$r = \frac{V_1}{V_2}$$

Constant Volume Heat Addition Process (2 – 3):

- Heat is added at constant volume from an external heat source.
- The pressure rises and the ratio $r_p \ or \ \alpha = \frac{p_3}{p_2}$ is called expansion ratio or pressure ratio.

Adiabatic Expansion Process (3 – 4):

- The increased high pressure exerts a greater amount of force on the piston and pushes it towards the BDC.
- Expansion of working fluid takes place isentropically and work done by the system.
- The volume ratio $\frac{V_4}{V_3}$ is called isentropic expansion ratio.

Constant Volume Heat Rejection Process (4 – 1):

- Heat is rejected to the external sink at constant volume. This process is so controlled that ultimately the working fluid comes to its initial state 1 and the cycle is repeated.
- Many petrol and gas engines work on a cycle which is a slight modification of the Otto cycle.
- This cycle is called constant volume cycle because the heat is supplied to air at constant volume.

Air Standard Efficiency of an Otto Cycle:

- Consider a unit mass of air undergoing a cyclic change.
- **Heat supplied** during the process 2 – 3,

$$q_1 = C_V\left(T_3 - T_2\right)$$

- **Heat rejected** during process 4 – 1 ,

$$q_2 = C_V\left(T_4 - T_1\right)$$

- **Work done,**

$$\therefore W = q_1 - q_2$$
$$\therefore W = C_V\left(T_3 - T_2\right) - C_V\left(T_4 - T_1\right)$$

- **Thermal efficiency,**

$$\eta = \frac{Work\,done}{Heat\,supplied} = \frac{W}{q_1}$$

$$= \frac{C_V\left(T_3 - T_2\right) - C_V\left(T_4 - T_1\right)}{C_V\left(T_3 - T_2\right)}$$

$$= 1 - \frac{\left(T_4 - T_1\right)}{\left(T_3 - T_2\right)} \qquad (1.12)$$

- For Adiabatic compression process (1 – 2),

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

$$\therefore \mathrm{T_2} = \mathrm{T_1 r}^{\gamma-1} \qquad (1.13)$$

- For Isentropic expansion process (3 – 4),

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1}$$

$$\therefore T_3 = T_4\left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

$$\therefore T_3 = \mathrm{T_4}\left(\frac{\mathrm{V_1}}{\mathrm{V_2}}\right)^{\gamma-1} \left(\because\ \mathrm{V_1} = \mathrm{V_4}, \mathrm{V_2} = \mathrm{V_3}\right)$$

$$\therefore T_3 = T_4\left(r\right)^{\gamma-1} \qquad (1.14)$$

- From equation 1.16, 1.17 & 1.18, we get,

$$\eta_{otto} = 1 - \frac{\left(T_4 - T_1\right)}{T_4\, r^{\gamma-1} - T_1\, r^{\gamma-1}}$$

$$\therefore \eta_{otto} = 1 - \frac{\left(T_4 - T_1\right)}{r^{\gamma-1}\left(T_4 - T_1\right)}$$

$$\therefore \eta_{otto} = 1 - \frac{1}{r^{\gamma-1}} \qquad (1.15)$$

- Expression 1.19 is known as the air standard efficiency of the Otto cycle.
- It is clear from the above expression that efficiency increases with the increase in the value of r (as γ is constant).
- We can have maximum efficiency by increasing r to a considerable extent, but due to practical difficulties its value is limited to 8.
- In actual engines working on Otto cycle, the compression ratio varies from 5 to 8 depending upon the quality of fuel.

- At compression ratios higher than this, the temperature after combustion becomes high and that may lead to spontaneous and uncontrolled combustion of fuel in the cylinder.
- The phenomenon of uncontrolled combustion in petrol engine is called detonation and it leads to poor engine efficiency and in structural damage of engine parts.

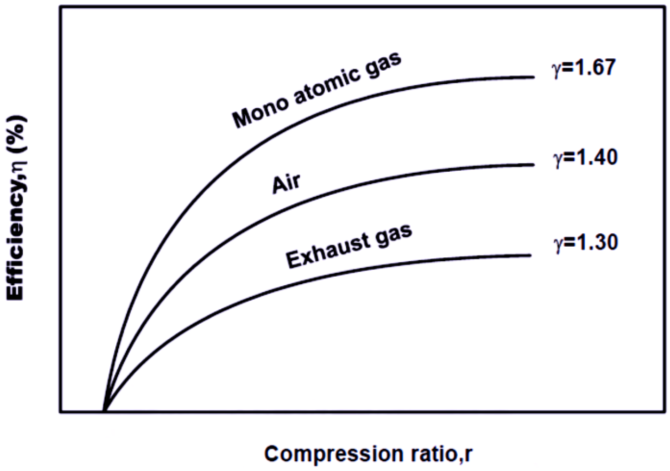


Fig. 1.12 Variation of Otto cycle efficiency with compression ratio

- Fig. 1.12 shows the variation of air standard efficiency of Otto cycle with compression ratio.

Mean Effective Pressure:

- **Net work done** per unit mass of air,

$$W_{net} = C_V\left(T_3 - T_2\right) - C_V\left(T_4 - T_1\right) \tag{1.16}$$

- **Swept volume,**

$$Swept\ volume = V_1 - V_2 = V_1\left(1 - \frac{V_2}{V_1}\right) = \frac{RT_1}{P_1}\left(1 - \frac{1}{r}\right)$$

$$= \frac{RT_1}{P_1 r}\left(r - 1\right) \tag{1.17}$$

- **Mean effective pressure,**

$$mep = \frac{Work\ done\ per\ cycle}{swept\ volume}$$

$$= \frac{C_V\left(T_3 - T_2\right) - C_V\left(T_4 - T_1\right)}{\frac{RT_1}{P_1 r}\left(r - 1\right)}$$

$$= \frac{C_V}{R}\frac{P_1 r}{\left(r - 1\right)}\left[\frac{\left(T_3 - T_2\right) - \left(T_4 - T_1\right)}{T_1}\right] \tag{1.18}$$

- For process 1 – 2,

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

$$\boldsymbol{T_2 = T_1 r^{\gamma-1}}$$

- Process 2 – 3,

$$\frac{T_3}{T_2} = \frac{P_3}{P_2} (\because$$

$$\therefore T_3 = T_2\,\alpha \qquad (\alpha = explosion\ pressure\ ratio)$$

$$\therefore \boldsymbol{T_3 = T_1\ \alpha\, r^{\gamma-1}}$$

- Process 3 – 4,

$$T_4 = T_3 \left(\frac{V_3}{V_4}\right)^{\gamma-1}$$

$$T_4 = T_3 \left(\frac{V_3}{V_4}\right)^{\gamma-1}$$

$$\therefore T_4 = T_1\ \alpha\ r^{\gamma-1} \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$\therefore T_4 = T_1\ \alpha\ r^{\gamma-1} \times \frac{1}{r^{\gamma-1}}$$

$$\therefore \boldsymbol{T_4 = T_1 \cdot \alpha}$$

- Substituting all these temperature values in equation 1.22, We get,

$$mep = \frac{C_V}{R} \frac{P_1 r}{(r-1)} \left[\frac{\left(T_1 \alpha\, r^{\gamma-1} - T_1 r^{\gamma-1}\right) - \left(T_1 \alpha - T_1\right)}{T_1} \right]$$

$$\therefore mep = \frac{C_V}{R} \frac{P_1 r}{(r-1)} \left[\frac{T_1 r^{\gamma-1}(\alpha-1) - T_1(\alpha-1)}{T_1} \right]$$

$$\therefore mep = \frac{C_V}{R} \frac{P_1 r}{(r-1)} \left[\left(r^{\gamma-1} - 1\right)(\alpha-1) \right]$$

$$\therefore mep = \frac{P_1 r}{(r-1)(\gamma-1)} \left[\left(r^{\gamma-1} - 1\right)(\alpha-1) \right] \tag{1.19}$$

$$\left(\because \frac{C_V}{R} = \frac{1}{\gamma-1}\right)$$

$$\begin{bmatrix} \dfrac{C_P}{C_V} = \gamma, & C_P - C_V = R, \\ C_V\left(\dfrac{C_P}{C_V} - 1\right) = R, & \dfrac{C_V}{R} = \dfrac{1}{\gamma-1} \end{bmatrix}$$

1.10.2 The Diesel Cycle ***OR*** Constant Pressure Cycle (Isobaric)

- This cycle was discovered by a German engineer Dr. Rudolph Diesel. Diesel cycle is also known as ***constant pressure heat addition cycle.***

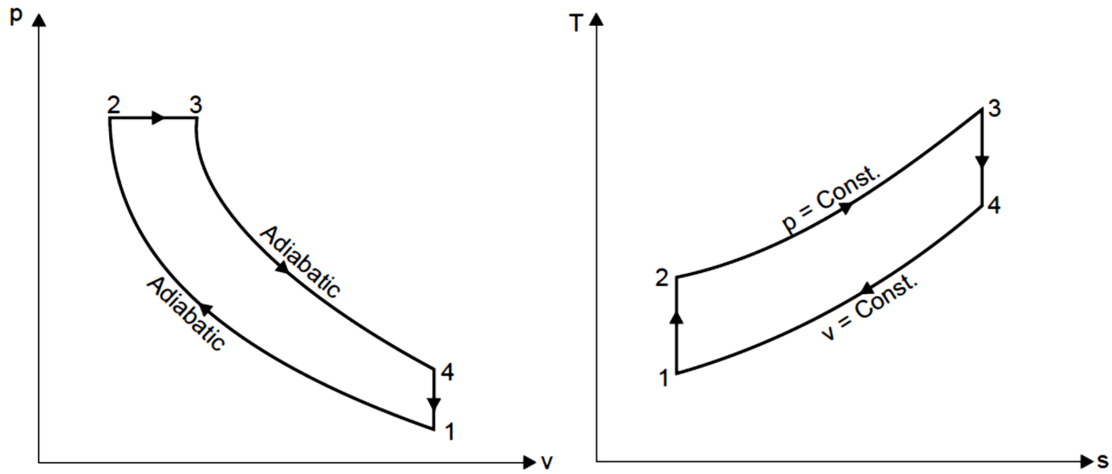


Fig. 1.13 p-V and T-s diagrams of Diesel cycle

Adiabatic Compression Process (1 – 2):

- Isentropic (Reversible adiabatic) compression with $r = \frac{V_1}{V_2}$.

Constant Pressure Heat Addition Process (2 – 3):

- The heat supply is stopped at point 3 which is called the cut – off point and the volume ratio $\rho = \frac{V_3}{V_2}$ is called **cut off ratio** or Isobaric expansion ratio.

Adiabatic Expansion Process (3 – 4):

- Isentropic expansion of air $\frac{V_4}{V_3} =$ isentropic expansion ratio.

Constant Volume Heat Rejection Process (4 – 1):

- In this process heat is rejected at constant volume.
- This thermodynamics cycle is called constant pressure cycle because heat is supplied to the air at constant pressure.

Air Standard Efficiency for Diesel Cycle:

- Consider unit mass of air.
- **Heat supplied** during process 2 – 3,

$$q_1 = C_P\left(T_3 - T_2\right)$$

- **Heat rejected** during process 4 – 1,

$$q_2 = C_V\left(T_4 - T_1\right)$$

- **Work done,**

$$W = q_1 - q_2$$
$$W = C_P(T_3 - T_2) - C_V(T_4 - T_1)$$

– **Thermal efficiency,**

$$\eta = \frac{Work\, done}{Heat\, supplied}$$
$$\therefore \eta = \frac{C_P(T_3 - T_2) - C_V(T_4 - T_1)}{C_P(T_3 - T_2)}$$
$$\therefore \eta = 1 - \frac{C_V}{C_P}\frac{(T_4 - T_1)}{(T_3 - T_2)}$$
$$\therefore \eta = 1 - \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)} \quad (1.20)$$

– For adiabatic compression process (1 – 2),

$$r = \frac{V_1}{V_2} \quad (1.21)$$
$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$
$$P_2 = P_1 \cdot r^{\gamma} \quad (1.22)$$
$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1} = T_1 r^{\gamma-1} \quad (1.23)$$

– For constant pressure heat addition process (2 – 3)

$$P_3 = P_2 = P_1 \cdot r^{\gamma} \quad (1.24)$$
$$\rho = \frac{V_3}{V_2}\ (Cutoff\ ratio) \quad (1.25)$$
$$T_3 = T_2\frac{V_3}{V_2} \quad (1.26)$$
$$= T_2 \cdot \rho$$
$$\therefore T_3 = T_1 \cdot r^{\gamma-1} \cdot \rho \quad (1.27)$$

– For adiabatic expansion process (3 – 4),

$$P_4 = P_3(V_3/V_4)^{\gamma} = P_3(V_3/V_1)^{\gamma}$$
$$\therefore P_4 = P_3\left(\frac{V_3/V_2}{V_1/V_2}\right)^{\gamma} = P_3(\rho/r)^{\gamma} \quad (1.28)$$
$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{\gamma-1} = T_3\left(\frac{\rho}{r}\right)^{\gamma-1}$$

$$\therefore T_4 = \frac{T_1 \cdot r^{\gamma-1} \cdot \rho \cdot \rho^{\gamma-1}}{r^{\gamma-1}}$$

$$\therefore T_4 = T_1 \cdot \rho^{\gamma} \tag{1.29}$$

- Using above equations in equation 1.24

$$\eta = 1 - \frac{1}{\gamma}\frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$\therefore \eta = 1 - \frac{1}{\gamma}\frac{(T_1 \rho^{\gamma} - T_1)}{(T_1 r^{\gamma-1}\rho - T_1 r^{\gamma-1})}$$

$$\therefore \boldsymbol{\eta} = 1 - \frac{1}{\boldsymbol{r}^{\gamma-1}}\left[\frac{(\boldsymbol{\rho}^{\gamma} - 1)}{\gamma(\boldsymbol{\rho} - 1)}\right] \tag{1.30}$$

- Apparently the efficiency of diesel cycle depends upon the compression ratio (r) and cutoff ratio (ρ) and hence upon the quantity of heat supplied.
- Fig. 1.14 shows the air standard efficiency of diesel cycle for various cut off ratio.
- Further,

$$K = \frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}$$

  reveals that with an increase in the cut – off ratio (ρ) the value of factor K increases.
- That implies that for a diesel engine at constant compression ratio, the efficiency would increase with decrease in ρ and in the limit $\rho \rightarrow 1$, the efficiency would become

$$1 - \frac{1}{r^{\gamma-1}}$$

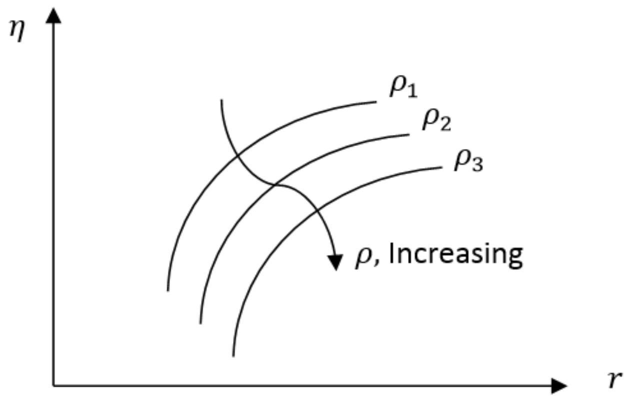


Fig. 1.14 Efficiency of Diesel cycle for various cut-off ratio

- Since the factor $K = \frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}$ is always greater than unity, the Diesel cycle is always less efficient than a corresponding Otto cycle having the same compression ratio.
- However Diesel engine operates on much higher compression ratio (14 to 18) compared to those for S.I. Engines operating on Otto cycle.
- High compression ratios for Diesel engines are must not only for high efficiency but also to prevent diesel knock; a phenomenon which leads to uncontrolled and rapid combustion in diesel engines.

Mean Effective Pressure:

– **Net work done** per unit mass of air,

$$W_{net} = C_p\left(T_3 - T_2\right) - C_V\left(T_4 - T_1\right) \tag{1.31}$$

– **Swept volume,**

$$Swept\,volume = V_1 - V_2 = V_1\left(1 - \frac{V_2}{V_1}\right) = \frac{RT_1}{P_1}\left(1 - \frac{1}{r}\right)$$

$$= \frac{RT_1}{P_1 r}\left(r - 1\right) \tag{1.32}$$

– **Mean effective pressure,**

$$mep = \frac{Work\,done\,per\,cycle}{swept\,volume}$$

$$\therefore mep = \frac{C_P\left(T_3 - T_2\right) - C_V\left(T_4 - T_1\right)}{\frac{RT_1}{P_1 r}\left(r - 1\right)}$$

$$\therefore mep = \frac{C_V}{R}\frac{P_1 r}{\left(r - 1\right)}\left[\frac{\gamma\left(T_3 - T_2\right) - \left(T_4 - T_1\right)}{T_1}\right] \tag{1.33}$$

– From equation 1.27, 1.31 and 1.33,

$T_2 = T_1 r^{\gamma - 1}$

$T_3 = T_1 r^{\gamma - 1}\rho$

$T_4 = T_1 \rho^{\gamma}$

$$\therefore mep = \frac{C_V}{R}\frac{P_1 r}{\left(r - 1\right)}\left[\frac{\gamma\left(T_1 r^{\gamma - 1}\rho - T_1 r^{\gamma - 1}\right) - \left(T_1 \rho^{\gamma} - T_1\right)}{T_1}\right]$$

$$\therefore \boldsymbol{mep} = \frac{\boldsymbol{P_1 r}}{\left(\boldsymbol{\gamma} - 1\right)\left(\boldsymbol{r} - 1\right)}\left[\boldsymbol{\gamma r^{\gamma - 1}}\left(\boldsymbol{\rho} - 1\right) - \left(\boldsymbol{\rho^{\gamma}} - 1\right)\right] \tag{1.34}$$

1.10.3 The Dual Combustion Cycle OR The Limited Pressure Cycle

– This is a cycle in which the addition of heat is partly at constant volume and partly at constant pressure.

Adiabatic Compression Process (1 – 2):

– Isentropic (Reversible adiabatic) compression with $r = \frac{V_1}{V_2}$.

Constant Volume Heat Addition Process (2 – 3):

– The heat is supplied at constant volume with explosion ratio or pressure ratio $\alpha = \frac{P_3}{P_2}$.

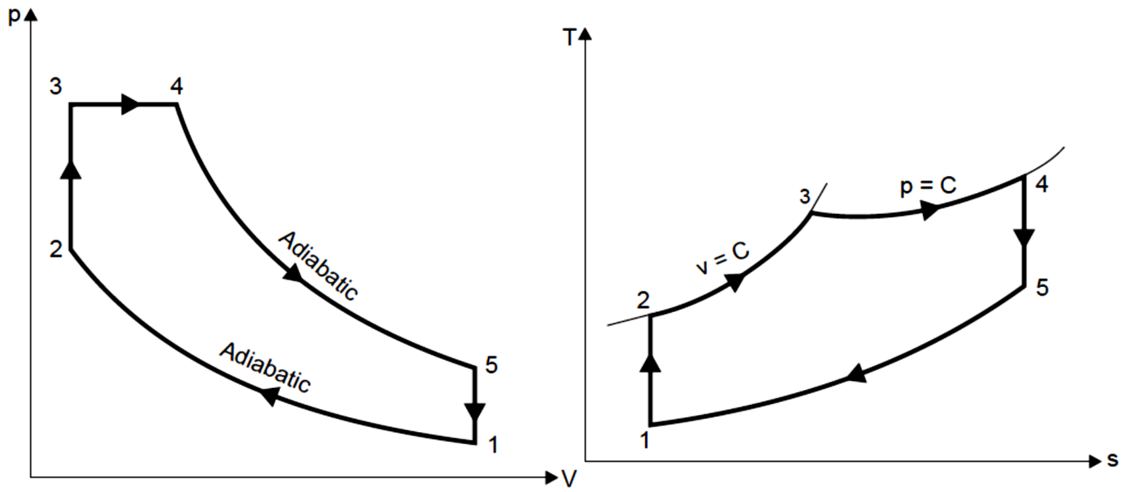


Fig. 1.15 p-V and T-s diagrams of Diesel cycle

Constant Pressure Heat Addition Process (3 – 4):

- The heat supply is stopped at point 4 which is called the cut – off point and the volume ratio $\rho = \frac{V_4}{V_3}$ is called **cut off ratio**.

Adiabatic Expansion Process (4 – 5):

- Isentropic expansion of air with $\frac{V_5}{V_4}$ = isentropic expansion ratio.

Constant Volume Heat Rejection Process (5 – 1):

- In this process heat is rejected at constant volume.
- The high speed Diesel engines work on a cycle which is slight modification of the Dual cycle.

Thermal Efficiency for Dual Cycle:

- Consider unit mass of air undergoing the cyclic change.
- **Heat supplied**,

$$q_1 = q_{2-3} + q_{3-4}$$
$$q_1 = C_V(T_3 - T_2) + C_P(T_4 - T_3)$$

- **Heat rejected** during process 5 – 1,

$$q_2 = C_V(T_5 - T_1)$$

- **Work done,**

$$W = q_1 - q_2$$
$$W = C_V(T_3 - T_2) + C_P(T_4 - T_3) - C_V(T_5 - T_1)$$

- **Thermal efficiency,**

$$\eta = \frac{Work\,done}{Heat\,supplied}$$

$$\therefore \eta = \frac{C_V\left(T_3 - T_2\right) + C_P\left(T_4 - T_3\right) - \mathrm{C_V}\left(\mathrm{T_5} - \mathrm{T_1}\right)}{C_V\left(T_3 - T_2\right) + C_P\left(T_4 - T_3\right)}$$

$$\therefore \eta = 1 - \frac{\left(T_5 - T_1\right)}{\left(T_3 - T_2\right) + \gamma\left(T_4 - T_3\right)} \qquad (1.35)$$

- For adiabatic compression process (1 – 2),

$$r = \frac{V_1}{V_2} \qquad (1.36)$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

$$P_2 = P_1 r^{\gamma} \qquad (1.37)$$

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma - 1} = T_1\, r^{\gamma - 1} \qquad (1.38)$$

- For constant volume heat addition process (2 – 3)

$$V_3 = V_2 = \frac{V_1}{r}$$

$$\alpha = \frac{P_3}{P_2}\ \left(Pressure\,ratio\right) \qquad (1.39)$$

$$\therefore P_3 = P_2 \cdot \alpha = P_1 \cdot r^{\gamma} \cdot \alpha$$

$$T_3 = T_2\,\frac{P_3}{P_2}$$

$$= T_2\,\alpha$$

$$\therefore T_3 = T_1\, r^{\gamma - 1}\alpha \qquad (1.40)$$

- For constant pressure heat addition process (3 – 4)

$$P_3 = P_4 = P_1 r^{\gamma}\alpha \qquad (1.41)$$

$$\rho = \frac{V_4}{V_3}\ \left(Cutoff\ ratio\right) \qquad (1.42)$$

$$T_4 = T_3\,\frac{V_4}{V_3}$$

$$\therefore T_4 = T_3\,\rho$$

$$\therefore T_4 = T_1\, r^{\gamma - 1}\rho\alpha \qquad (1.43)$$

- For adiabatic expansion process (4 – 5),

$$P_4 V_4^{\gamma} = P_5 V_5^{\gamma}$$

$$P_5 = P_4 (V_4 / V_5)^{\gamma} = P_3 (V_4 / V_1)^{\gamma} \qquad (\because \qquad \& P_3 = P_4)$$

$$P_5 = P_3 \left(\frac{V_4}{V_1} \frac{V_3}{V_3} \right)^{\gamma} = P_3 \left(\frac{V_4}{V_1} \frac{V_2}{V_3} \right)^{\gamma} \qquad (\because$$

$$\therefore P_5 = P_3 \left(\frac{V_4 / V_3}{V_1 / V_2} \right)^{\gamma} = P_3 (\rho / r)^{\gamma} --------(i) \qquad (1.44)$$

and

$$T_5 = T_4 \left(\frac{V_4}{V_5} \right)^{\gamma-1}$$

$$\therefore T_5 = T_4 \left(\frac{\rho}{r} \right)^{\gamma-1}$$

$$\therefore T_5 = \frac{T_1 r^{\gamma-1} \rho\alpha \rho^{\gamma-1}}{r^{\gamma-1}}$$

$$\therefore T_5 = T_1 \alpha \rho^{\gamma} \qquad (1.45)$$

- From equation 1.39,

$$\eta = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma (T_4 - T_3)}$$

$$\therefore \eta = 1 - \frac{(T_1 \alpha \rho^{\gamma} - T_1)}{(T_1 r^{\gamma-1} \alpha - T_1 r^{\gamma-1}) + \gamma (T_1 r^{\gamma-1} \alpha\rho - T_1 r^{\gamma-1} \alpha)}$$

$$\therefore \eta = 1 - \frac{(\rho^{\gamma} \alpha - 1)}{\left[r^{\gamma-1} \{ (\alpha - 1\alpha) + \gamma\alpha (\rho - 1) \} \right]}$$

$$\therefore \boldsymbol{\eta} = 1 - \frac{1}{\boldsymbol{r}^{\gamma-1}} \left[\frac{(\boldsymbol{\alpha\rho}^{\gamma} - 1)}{(\boldsymbol{\alpha} - 1) + \boldsymbol{\gamma\alpha} (\boldsymbol{\rho} - 1)} \right] \qquad (1.46)$$

- It can be seen from the equation 1.50 that the thermal efficiency of a Dual cycle can be increased by supplying a greater portion of heat at constant volume (high value of α) and smaller portion at constant pressure (low value of ρ).
- In the actual high speed Diesel engines operating on this cycle, it is achieved by early fuel injection and an early cut-off.
- It is to be noted that Otto and Diesel cycles are special cases of the Dual cycle.
- If $\rho = 1$ $(V_3 = V_4)$
- Hence, there is no addition of heat at constant pressure. Consequently the entire heat is supplied at constant volume and the cycle becomes the Otto cycle.
- By substituting $\rho = 1$ in equation 1.50, we get,

$$\eta = 1 - \frac{1}{r^{(\gamma-1)}} = Efficiency\ of\ Otto\ cycle$$

- Similarly if $\alpha = 1$, the heat addition is only at constant pressure and cycle becomes Diesel cycle.

- By substituting $\alpha = 1$ in equation 1.50, we get,

$$\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{(\rho^{\gamma} - 1)}{\gamma(\rho - 1)}\right] = Efficiency\ of\ Diesel\ cycle$$

- <u>**Mean Effective Pressure:**</u>

- **Net work done** per unit mass of air,

$$W_{net} = C_V\left(T_3 - T_2\right) + C_p\left(T_4 - T_3\right) - C_V\left(T_5 - T_1\right) \quad (1.47)$$

- **Swept volume,**

$$\text{Swept Volume } = V_1 - V_2 = V_1\left(1 - \frac{V_2}{V_1}\right) = \frac{RT_1}{P_1}\left(1 - \frac{1}{r}\right)$$

$$= \frac{RT_1}{P_1 r}\left(r - 1\right) \quad (1.48)$$

- **Mean effective pressure,**

$$mep = \frac{Work\ done\ per\ cycle}{swept\ volume}$$

$$\therefore mep = \frac{C_V\left(T_3 - T_2\right) + C_p\left(T_4 - T_3\right) - C_V\left(T_5 - T_1\right)}{\frac{RT_1}{P_1 r}\left(r - 1\right)}$$

$$\therefore mep = \frac{C_V}{R}\frac{P_1 r}{\left(r - 1\right)}\left[\frac{\left(T_3 - T_2\right) + \gamma\left(T_4 - T_3\right) - \left(T_5 - T_1\right)}{T_1}\right]$$

- From equation 1.42, 1.44, 1.47 and 1.49,

$T_2 = T_1 \cdot r^{\gamma-1}$

$T_3 = T_1 \cdot r^{\gamma-1} \cdot \alpha$

$T_4 = T_1 \cdot r^{\gamma-1} \cdot \alpha \cdot \rho$

$T_5 = T_1 \cdot \alpha \cdot \rho^{\gamma}$

$$\therefore mep = \frac{C_V}{R}\frac{P_1 r}{\left(r - 1\right)}\left[\frac{\gamma\left(T_1 r^{\gamma-1}\alpha - T_1 r^{\gamma-1}\right) + \gamma\left(T_1 r^{\gamma-1}\alpha\rho - T_1 r^{\gamma-1}\alpha\right) - \left(T_1\alpha\rho^{\gamma} - T_1\right)}{T_1}\right]$$

$$\therefore \boldsymbol{mep} = \frac{\boldsymbol{P_1 r}}{\left(\boldsymbol{\gamma} - 1\right)\left(\boldsymbol{r} - 1\right)}\left[\left(\boldsymbol{\alpha} - 1\right)\boldsymbol{r}^{\gamma-1} + \boldsymbol{\gamma\alpha r}^{\gamma-1}\left(\boldsymbol{\rho} - 1\right) - \left(\boldsymbol{\alpha\rho}^{\gamma} - 1\right)\right] \quad (1.49)$$