INTERNAL COMBUSTION ENGINES

Syllabus

1. Engine classification and engine components.
2. Air standard cycles.
3. Cycles having the Carnot efficiency.
4. Comparison of Otto, Diesel and dual cycles.
5. Fuel- Air cycles; variation of specific heats.
6. Fuel- Air cycles; effect of engine variables.
7. Internal combustion engines fuels.
8. Combustion; basic chemistry.
9. Combustion; stoichiometry.
10. Combustion; exhausts gas analysis.
11. Combustion; Dissociation.
12. Combustion; internal energy, enthalpy of combustion and enthalpy of formation, and calorific value of fuels.
13. Real cycles.
14. Spark ignition engine and its components.
15. Compression ignition engine and its components.
16. Four stroke engine.
17. Two stroke engine
18. Scavenging in two - stroke engines.
19. Rotary engines; Gas turbine.
20. Rotary engines; Wankel engine.
21. Engine testing and performance; performance parameters.
22. Performance characteristics.
23. Testing and basic measurement of I.C. engines.
24. Supercharging and its effect on engine performance.

25. Turbo - charging.

26. I.C.E. fuel systems, carburation, fuel injection.

27. Valves (ports) timing.

28. Firing order.

References:

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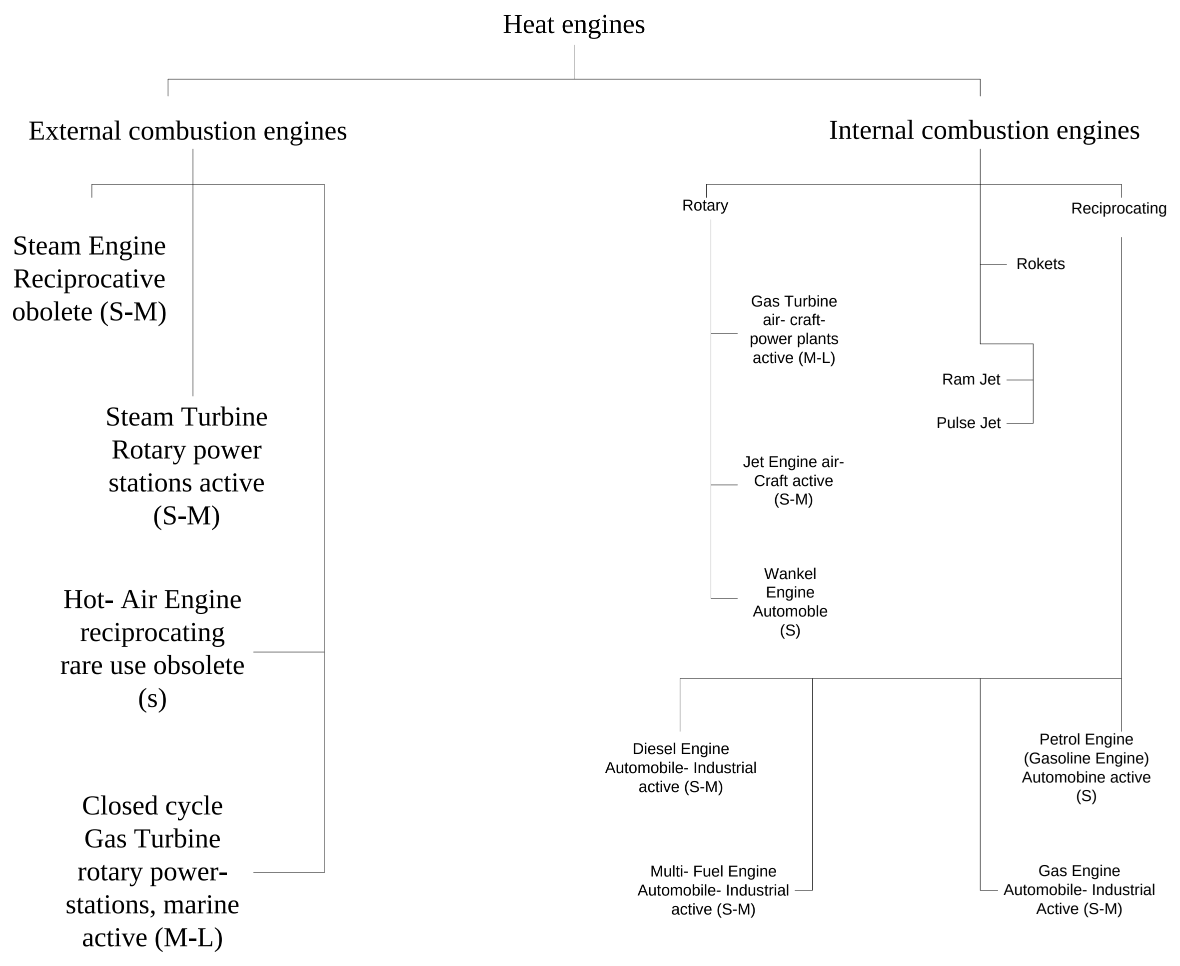
CHAPTER (1)

ENGINE CLASSIFICATION

Classification of Heat Engines:



L: Large over 10000 KW
M: Medium between 1000- 10000 KW
S: Small under 1000 KW

Figure (1-1): *Engine Classification*

Heat engines can be classified as; external combustion type in which the working fluid is entirely separated from the fuel- air mixture (ECE), and the internal - combustion (ICE) type, in which the working fluid consists of the products of combustion of the fuel- air mixture itself.

Comparison between the Different Kinds:

1. The Reciprocation Piston Engine:

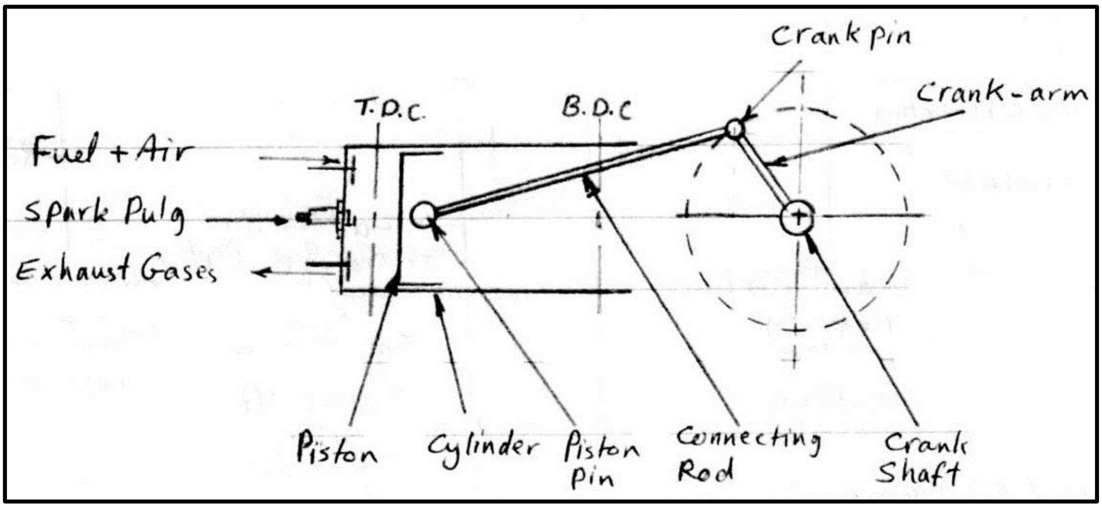


Figure (1-2): *Diagrammatic representation of reciprocating piston engine*

2. Open Cycle Gas Turbine:

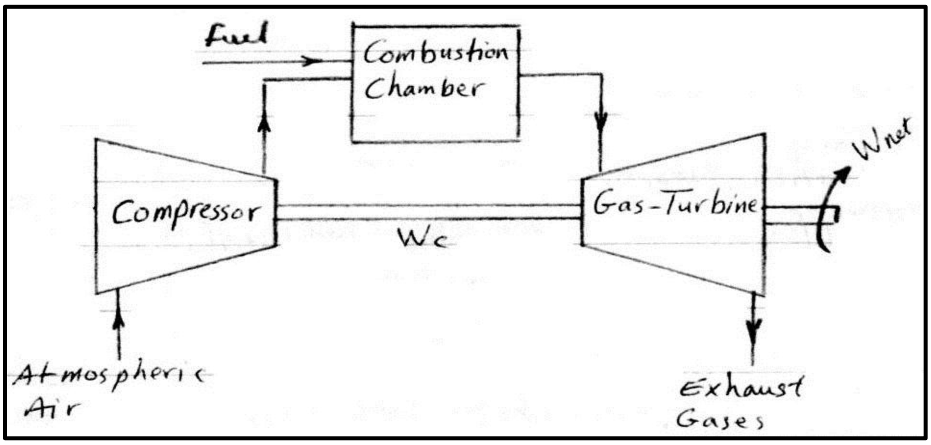


Figure (1-3): *Diagrammatic representation of gas turbine*

3. The Wankel Engine:

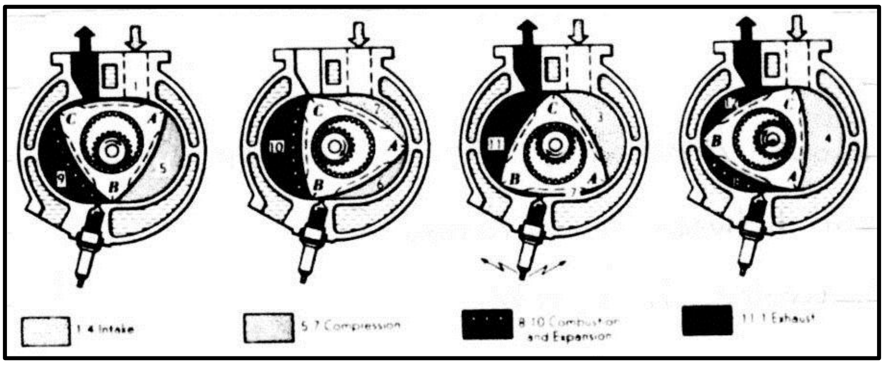
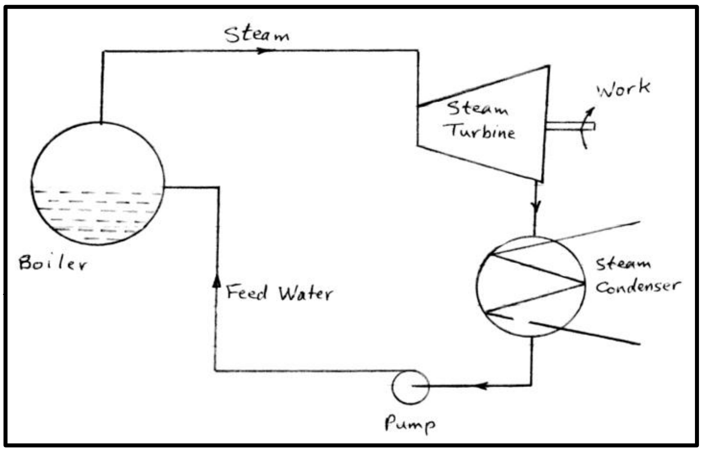


Figure (1-4): *Wankel four- process cycle*

4. Steam Power Plant:

Figure (1-5):



The Reciprocating I.C.E. is one unit and does not need other devices, the efficiency of the engine is relatively high, and the fuel used is relatively expensive.

The gas turbine group needs a compressors, its weight is smaller than reciprocating I.C.E. of the same power, its efficiency is lower, the fuel relatively cheap, and it is suitable for air craft.

Rotary engine is a substitute for the reciprocating I.C.E. Wankel engine has a three lobe rotor which is driven eccentrically in a casing in such a way that there are three separate volumes trapped between the rotor and the casing. These volumes perform induction, compression, combustion, expansion and exhaust process in sequence. This design has a good power/volume ratio. Seal wear and heat transfer, were some of the initial development problems of the Wankel engine. These problems have now been largely solved.

The steam turbine is suitable for very large powers, its efficiency is reasonable; the fuel used in the boiler is cheep. The steam turbine needs a boiler, condenser and a continuous supply of water.

Modern Developments of I.C.E.:

The modern I.C.E. is a product of research and developments extending over a long period of time many engines were proposed and tested, these include:

1. Stratified charge engine.
2. Dual Fuel and Multi- Fuel engines.
3. Sterling engine.
4. Free Piston engine.
5. Variable compression Ratio engine.
6. Combination of reciprocating engine with gas turbine.

Advantages of I.C.E. over E.C.E.:

1. More mechanical simplicity and lower weight/power ratio.
2. They do not need auxiliary equipment, such as boiler & condenser.
3. They could be started and stopped in a short time.
4. Their thermal efficiency is higher than other heat engines.
5. Their initial cost is low.

These advantages make I.C.E. more suitable in the transport sector; motor cars, small ships, submarines, and small aircrafts.

Types of Internal Combustion Engines:

I.C.E. can be divided into several groups according different features as characteristics: operating cycles, method of charging the cylinder, fuel used, general design (position and number of cylinders, method of ignition, rotating speed, etc.), and method of cooling the engine.

Fuel Used:

1. **Liquid Fuels**
   a. Volatile liquid fuels: petrol, Alcohol, benzene. Fuel /Air mixture is usually ignited by a spark; Spark ignition.
   b. Viscous liquid fuels: fuel oil, heavy and light diesel oil, gas-oil, bio-fuels. Usually combustion of fuel takes place due to its contact with high temperature compressed air (self-ignition); Compression ignition.
2. **Gaseous fuels:** Liquid Petroleum Gas (LPG), Natural gas (NG), Town gas, Blast Furnace gas; ignition usually by a spark.
3. **Dual and Multi-Fuels:**

Dual fuel engines are operated with two types of fuels, either separately or mixed together. Multi-fuel engines could be operated by a mixture of more than two fuels, gaseous; such as: Hydrogen, methane, L.P.G. etc., combined with one or more of liquid fuels, such as alcohol, ethers, esters, gasoline, diesel etc...

Method of Charging the Engine:

1. Naturally aspirated engine: Admission of charge at near atmospheric pressure.
2. Supercharged engine: Admission of charge at a pressure above atmospheric.

Number of Piston Stroke to Complete the Thermodynamic Cycle:

1. Four stroke engines: the cycle of operation is completed in four strokes of the piston or two revolution of the crank shaft. Each stroke consists of 180° of crank shaft rotation. The series of operations are shown in figure(1 – 6):

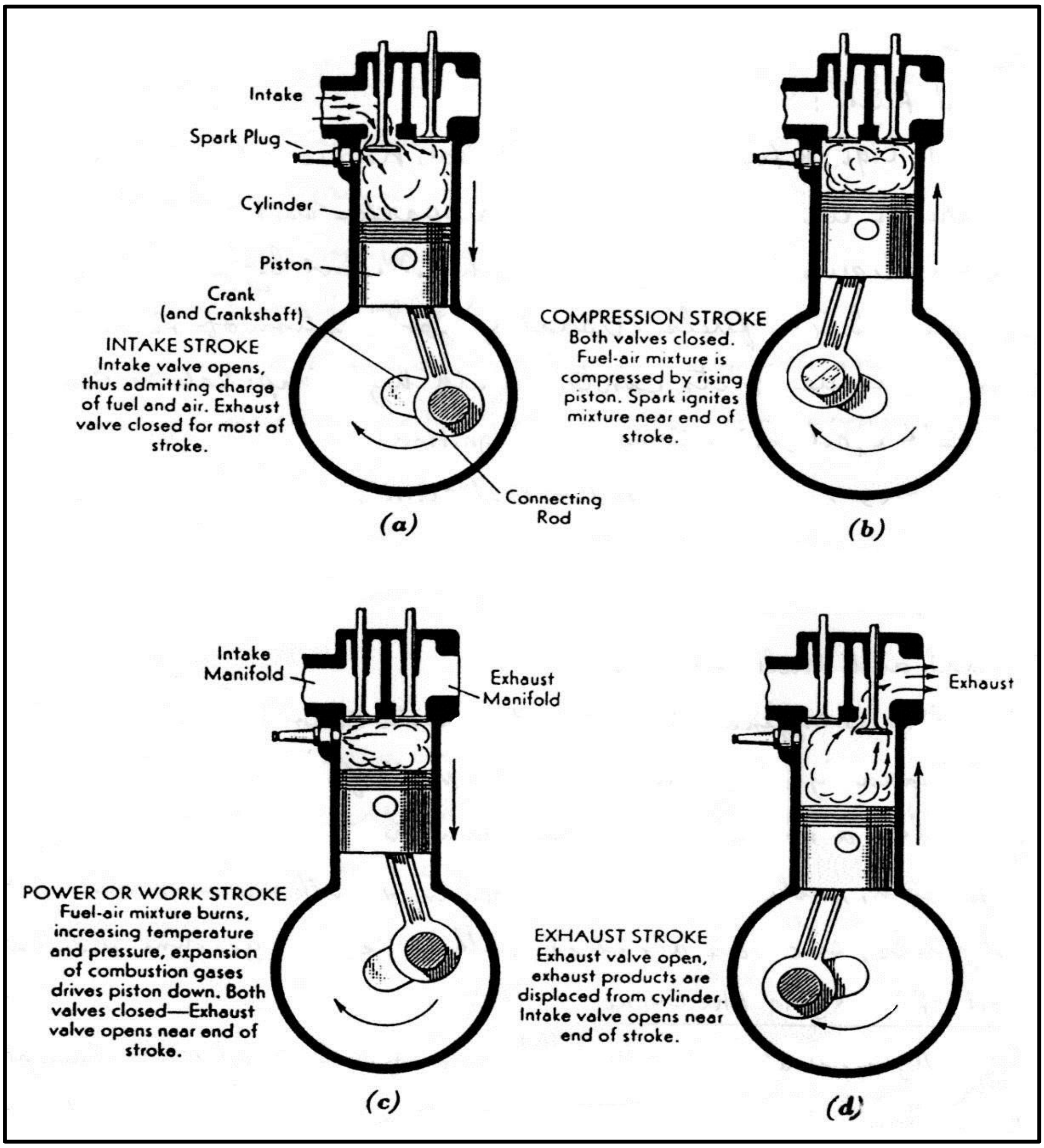


Figure (1-6): *Cylinder events of four- stroke cycle*

2. Two strokes engine: In two-stroke engine the cycle is completed in two strokes, i.e. one revolution of the crank shaft. The difference between two-stroke and four-stroke engines is in the method of filling the cylinder with the fresh charge and removing the products of combustion. The sequence of events shown in figure (1 – 7):

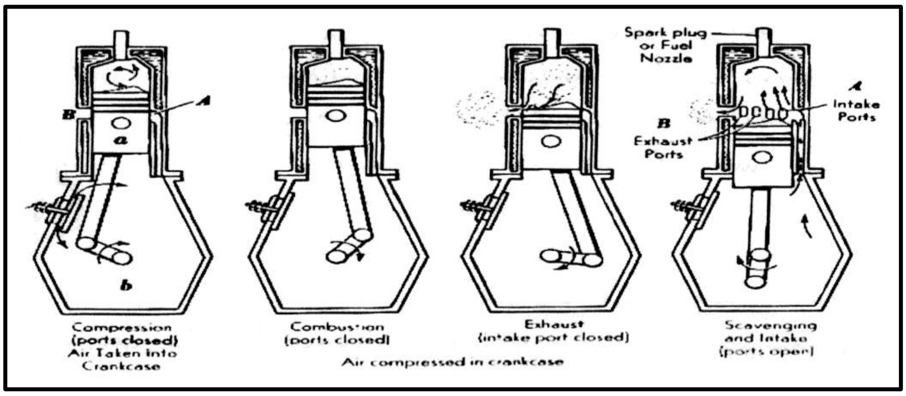


Figure (1-7): *Cylinder events of two- stroke cycle*

Cylinders Arrangement:

1. In- line engines: all cylinders are arranged linearly figure (1 – 8).
2. "V" engines: cylinders are in two banks inclined at an angle to each other and with one crank-shaft figure (1 – 8).
3. Opposed cylinder banks located in the same plane on opposite sides of the crank-shaft figure (1 – 8).
4. Opposed piston engine: when a single cylinder houses two pistons, each of which drives a separate crank shaft figure (1 – 8).
5. Radial engine: the radial engine is an engine with more than two cylinders in each row equally spaced around the crank shaft. Normally it is been used in air-crafts figure (1 – 8).

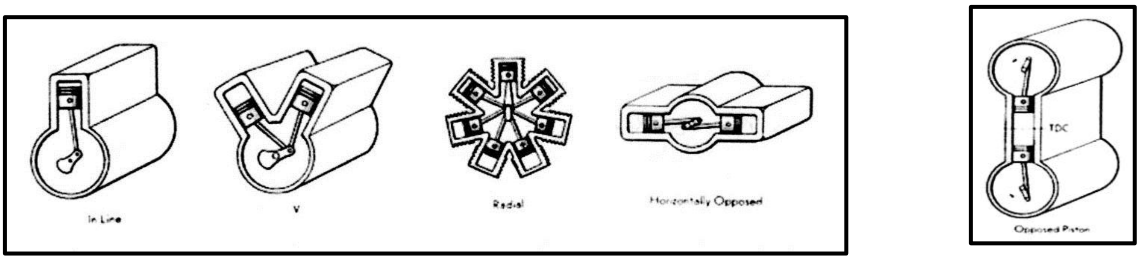


Figure (1-8): *Classification of engines by cylinder arrangement*

1. Double- acting engine: the fuel burns on both sides of the piston figure (1 – 8).
2. Cylinders may be vertical or horizontal, vertical engines needs smaller area, when area is available horizontal engines may be used, this would make all engine parts accessible and the operation and maintenance are easier.

Classification by valves Location:

The most popular design is the overhead-valve design, there are also an under head valve engines and a combination of the two designs is also used see figure (1 – 9).

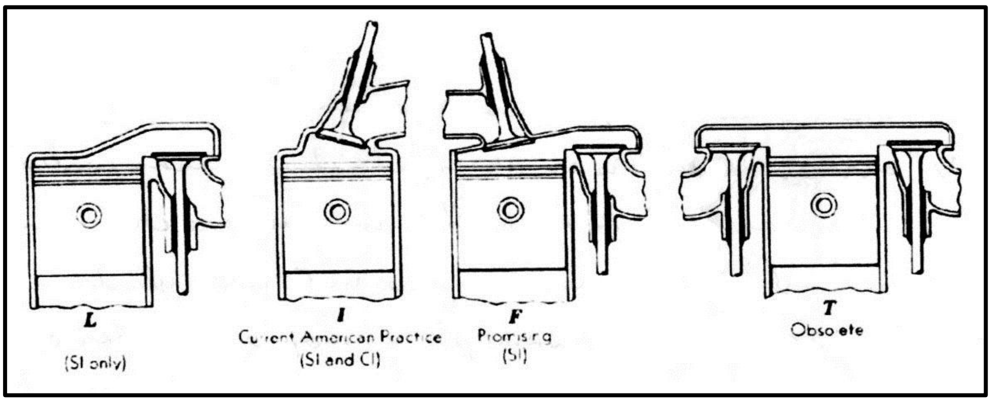


Figure (1-9): Classification of engines by valve location

Use of the Engine:

1. Marine engine: for propulsion of ships at sea.
2. Industrial engine: for power generation on land.
3. Automotive engine: for transport.

Method of Cooling the Engine:

1. Water- cooled engines.
2. Air- cooled engines.

The Continuous- Combustion Gas Turbine:

The main components of the gas turbine are; a compressor, a turbine and a combustion chamber, see figure (1 – 10). In operation, air is drawn into the compressor, compressed, and then passed, in part, through the combustion chamber. The high- temperature gases leaving the combustion chamber mix with the main body of air flowing around the combustor. This hot gas, with greatly increased volume, is led to a nozzle ring where the pressure is decreased and therefore the velocity is increased. The high- velocity gas is directed against the turbine wheel and the K.E. of the gas is utilized in turning the drive shaft, which also drives the air compressor.

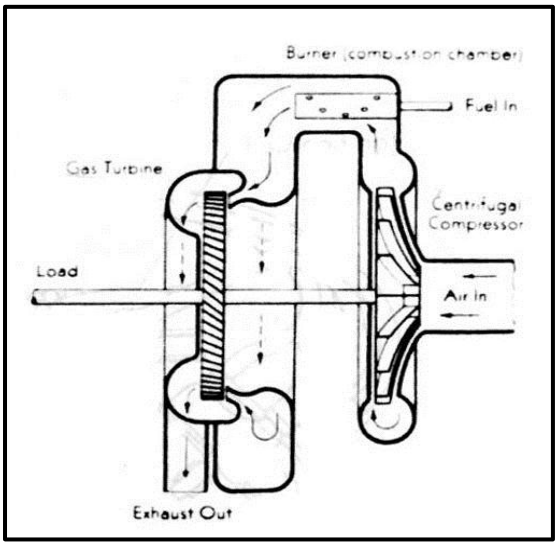


Figure (1-10): *Diagrammatic sketch of gas turbine*

I.C.Engine Parts and Details:

The main components of the reciprocating internal combustion engine are shown in Figure (1-11). Engine parts are made of various materials and perform certain functions, some of which will be explained: cylinder block (g) it is integral with crank case (m), both are made of cast iron. The piston (e) reciprocates inside the cylinder, which include the combustion chamber.

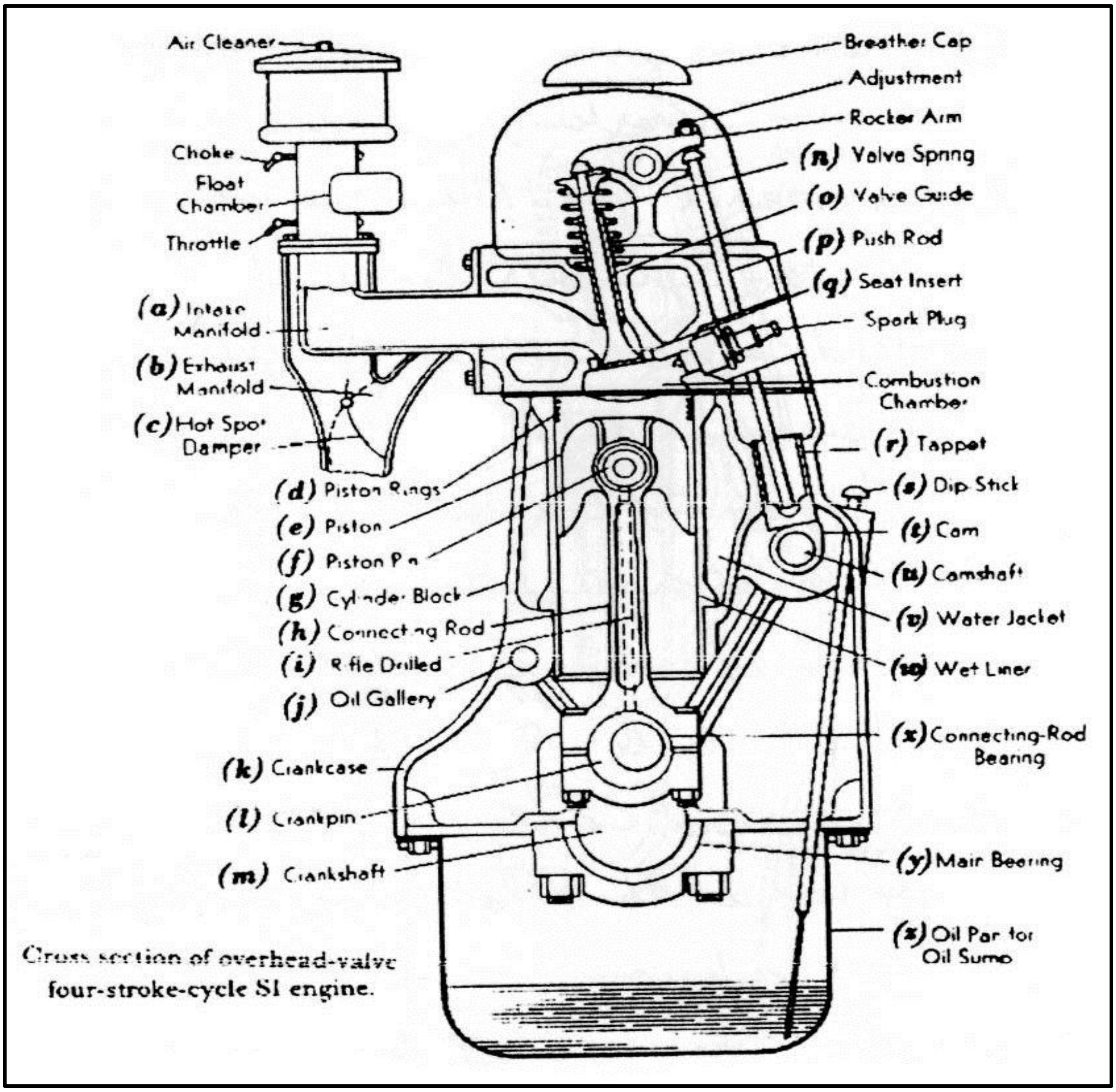


Figure (1-11): S.I.engine parts and details

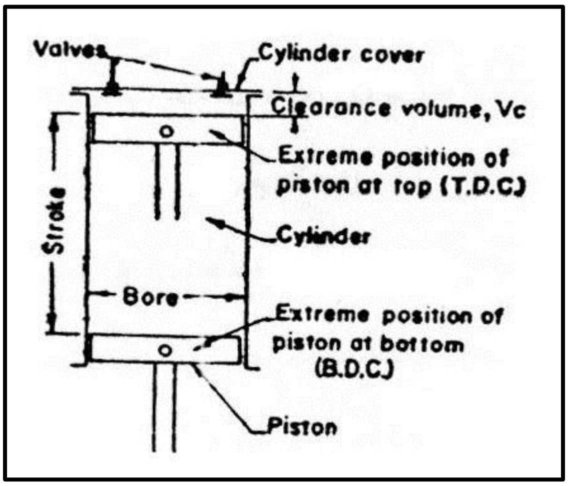
The piston is connected to the connecting rod (h) by piston pin (f). This end of the connecting rod is known as small end. The other end of the connecting rod called the big end is connected to the crank arm by crank pin (l).

Camshaft (u) makes the cam (t) to rotate and move up and down the valve rod through the tappet (r). Mainly each cylinder has two valves; one is admission or suction valve and the other is exhaust valve.

The ignition system consists of a battery, an ignition coil, a distributor with cam and breaker points, and spark plug for each cylinder. In diesel engines there is an injection system instead of ignition system.

Internal Combustion Engines Terminology:

1. Cylinder bore (B): The nominal inner diameter of the working cylinder.
2. Piston area (A): the area of a circle diameter equal to the cylinder bore.
3. Top Dead Center (T.D.C.): the extreme position of the piston at the top of the cylinder. In the case of the horizontal engines this is known as the outer dead center (O.D.C.).



4. Bottom Dead Center (B.D.C.): the extreme position of the piston at the bottom of the cylinder. In horizontal engine this is known as the Inner Dead Center (I.D.C.).
5. Stroke: the distance between TDC and BDC is called the stroke length and is equal to double the crank radius (l).
6. Swept volume: the volume swept through by the piston in moving between TDC and is denoted by Vs:

$$Vs = \frac{\pi}{4} d^2 \times l$$

Where d is the cylinder bore and l the stroke.

1. Clearance volume: the space above the piston head at the TDC, and is denoted by Vc:

   Volume of the cylinder: $V = Vc + Vs$

2. Compression ratio: it is the ratio of the total volume of the cylinder to the clearance volume, and is denoted by (r)

$$r = \frac{V}{Vc} = \frac{Vc + Vs}{Vc}$$

3. Mean piston speed: the distance traveled by the piston per unit of time:

$$V_m = \frac{2lN}{60} m/s$$

Where l is the stroke in (m) and N the number of crankshaft revolution per minute (rpm).

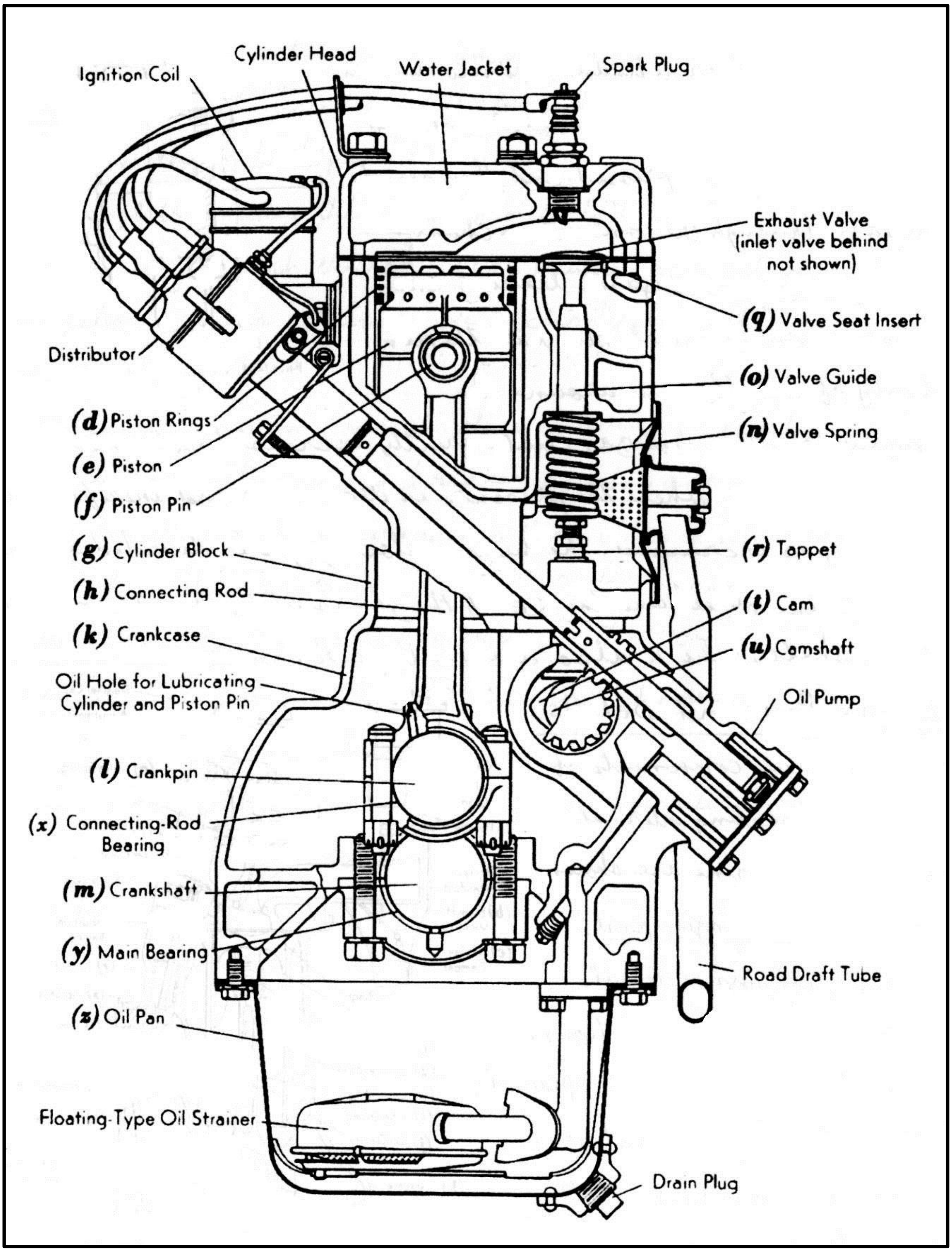


Figure (1-12): *Piston and cylinder geometry*

CHAPTER (2)

Air Standard Cycles

During every engine cycle, the medium changes sometimes it is a mixture of fuel and air or products of combustion, the specific heats and other properties of the medium change with temperature and composition.

The accurate study and analysis of I.C.E. processes is very complicated. To simplify the theoretical study "Standard Air Cycles" are introduced, these cycles are similar to the open cycles, but some simplifying assumptions are made:

1. Cylinder contains constant amount of air and it is treated as ideal gas.
2. The specific heats and other physical and chemical properties remain unchanged during the cycle.
3. Instead of heat generation by combustion, heat is transformed from external heat source.
4. The process of heat removal in the exhaust gases is represented by heat transfer from the cycle to external heat sink.
5. There is neither friction nor turbulence; all processes are assumed to be reversible.
6. No heat loss from the working fluid to the surroundings.
7. Cycles can be presented on any diagram of properties.

The Otto Cycle (constant Volume):

These cycles is applied in petrol (or gasoline) engine, gas engine, and high speed diesel (oil) engine. The cycle is shown in Figure (1 – 13), and consists of the following processes:

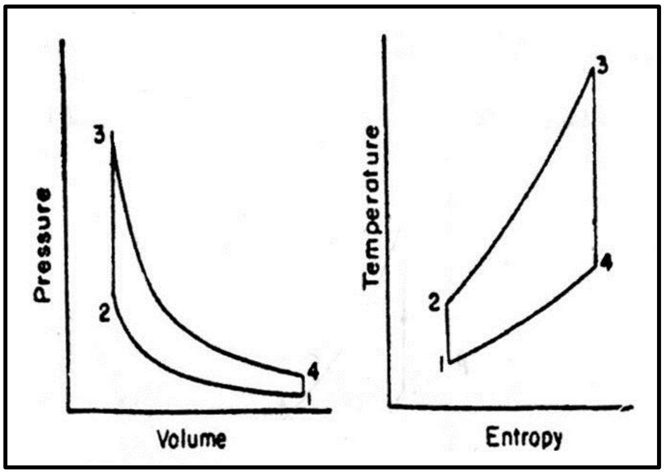


Figure (1-13)

1. Process 1 to 2 is isentropic compression;

$Q_{12} = 0.$

2. process 2 to 3 is reversible heat addition at constant volume

$$Q_{23} = C_v\,(T_3 - T_2)\ \text{kJ/kg}$$

3. process 3 to 4 is isentropic expression;

$Q_{34} = 0$

4. process 4 to 5 is reversible constant volume cooling

$Q_{41} = C_v (T_4 - T_1)$ kj/ kg

This cycle is applied in 4- stroke and 2- stroke engines.

Work of Otto cycle = $W_{34} - W_{12}$

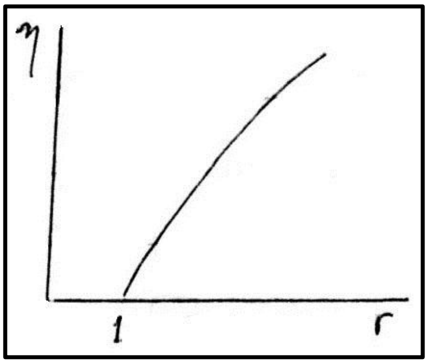
The thermal efficiency of the Otto cycle $\eta = \frac{Q^{\uparrow} - Q^{\downarrow}}{Q^{\downarrow}} = 1 - \frac{Q^{\uparrow}}{Q^{\downarrow}}$

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

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{V_4}{V_3}\right)^{\gamma-1} = \frac{T_3}{T_4} = r^{\gamma-1}$$

$T_3 = T_4 = r^{\gamma-1}$ and $T_2 = T_1 r^{\gamma-1}$

$$\therefore \eta = 1 - \frac{T_4 - T_1}{(T_4 - T_1) r^{\gamma-1}} = 1 - \frac{1}{r^{\gamma-1}}$$



η increased by increasing r

η increased by increasing γ

η independent on the heat added or load.

In modern petrol engines r reaches a value of 12.

To make use of that part of the energy in the exhaust gases, they may be expanded to atmospheric pressure in an exhaust gas turbine; the work of the cycle will be increased by the aria $144\bar{4}1$ as shown in figure (1-14). The new cycle $(12344\bar{4}1)$ is called Atkinson cycle, this cycle is applied in a combination of petrol engine and gas turbine, the turbine in usually used to drive a compressor to supercharge the engine.

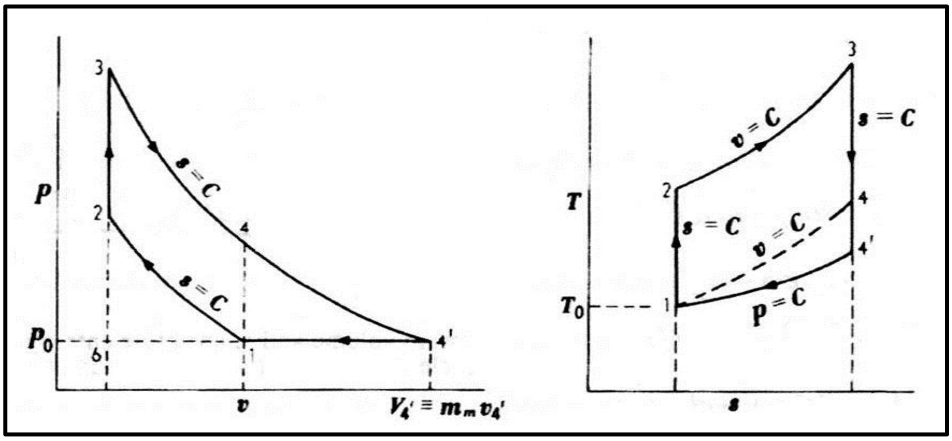


Figure (1-15): *Air- standard complete- expansion cycle*

The Diesel (or Constant Pressure) Cycle:

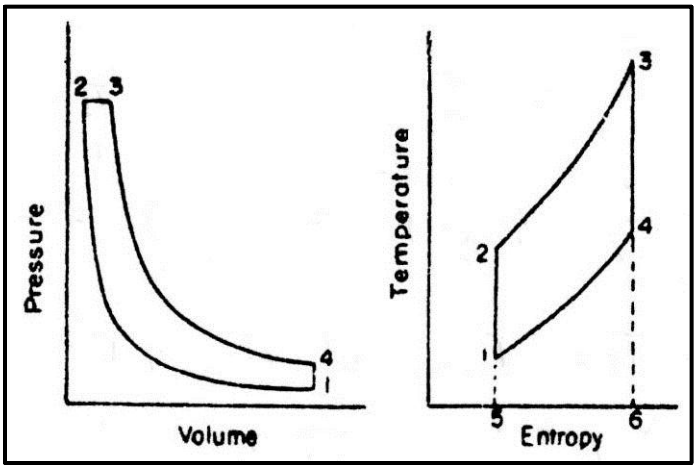


Figure (1-16): *pressure volume and temperature entropy diagram of a cycle with constant pressure heat addition*

This cycle is the theoretical cycle for compression-ignition or diesel engine. For this cycle:

$Q_1 = C_p\,(T_3 - T_2)$

$Q_2 = C_v\,(T_4 - T_1)$

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{1}{\gamma}\left(\frac{T_4 - T_1}{T_3 - T_2}\right) = 1 - \frac{T_1}{\gamma T_2}\left(\frac{\frac{T_4}{T_2} - 1}{\frac{T_3}{T_2} - 1}\right)$$

For isentropic compression and expansion:

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

For constant Pressure heat addition 2-3: $\dfrac{T_3}{T_2} = \dfrac{v_3}{v_2}$

Thus:

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

By substitution:

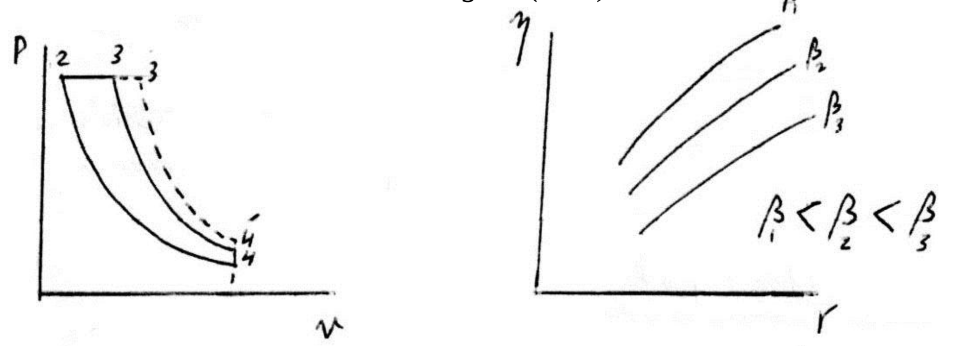
$$\eta = 1 - \frac{1}{\gamma\left(\frac{v_1}{v_2}\right)^{\gamma-1}}\left(\frac{\left(\frac{v_3}{v_2}\right)^{\gamma} - 1}{\left(\frac{v_3}{v_2}\right) - 1}\right)$$

$$\frac{v_1}{v_2} = r \quad \text{and} \quad \frac{v_3}{v_2} = \beta \text{, then:}$$

$$\eta = 1 - \frac{\beta^{\gamma} - 1}{(\beta - 1)\gamma\, r^{\gamma - 1}}$$

This equation shows that thermal efficiency depends not only on r but also on the cut-off ratio $\left(\beta = \frac{v_3}{v_2}\right)$ and the working medium properties γ. As β increase the work done per cycle increase but η decreases. When r increase more than 22, the increase in η is small, on the other hand, maximum pressure increases much and mass of the engine increases.

Figure (1-17)



The Dual Cycle:

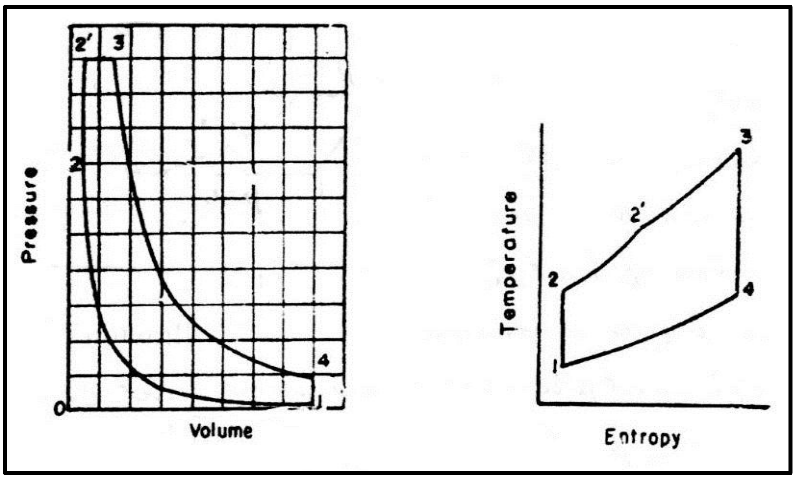


Figure (1-18): *Pressure-Volume and Temperature-Entropy diagram of dual cycle*

The cycle is applied in medium speed and high speed diesel engines. The engine may be 4 or 2 strokes

$$Q_1 = Q_1' + Q_1''$$

$$= C_v\left(T_2' - T_2\right) + C_p\left(T_3 - T_{2'}\right)$$

$$Q_2 = C_v\left(T_4 - T_1\right)$$

$$\eta = 1 - \frac{Q_2}{Q_1}$$

It can be proved that:

$$\eta = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{k\beta^{\gamma} - 1}{(k-1) + \gamma k(\beta - 1)}\right]$$

$$k = \frac{p_{2'}}{p_2} \quad \text{and} \quad \beta = \frac{V_3}{V_{2'}}$$

When k = 1, then $p_{2'} = p_2$, we obtain diesel cycle. When $\beta = 1$, then $V_3 = V_{2'}$, we obtain Otto cycle. The indicated thermal efficiency of this cycle lies between that of the Otto and diesel.

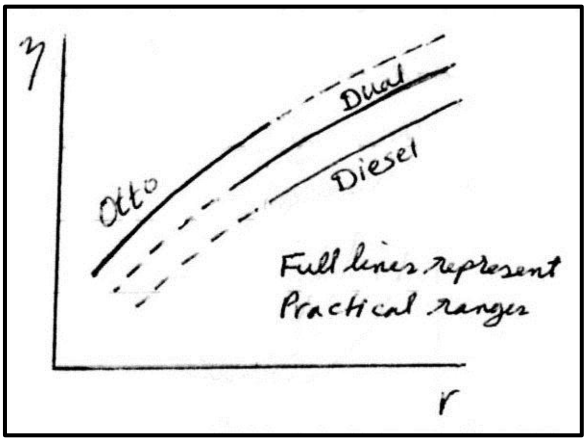


Figure (1-19)

Joule (or Brayton) Cycle:

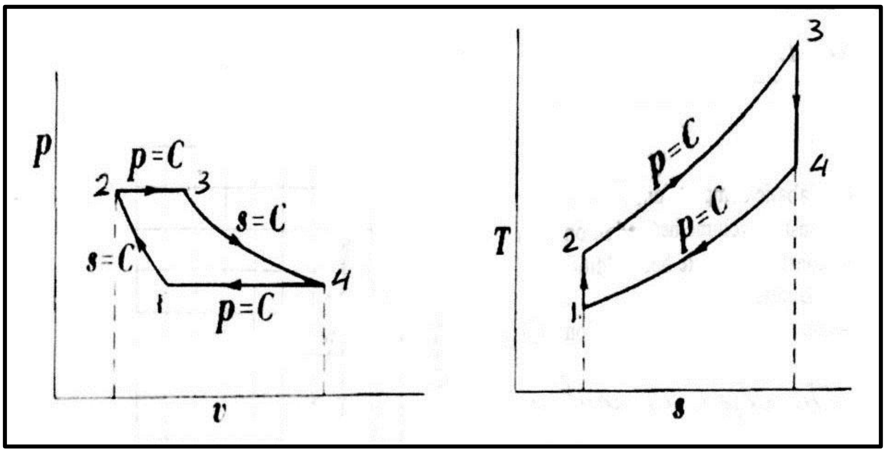


Figure (1-20): *Brayton (Joule) air- standard cycle*

This cycle is used in gas turbine, it consists of:

ab: isentropic compression.

bc: constant pressure addition of heat Q_1.

cd: isentropic expansion.

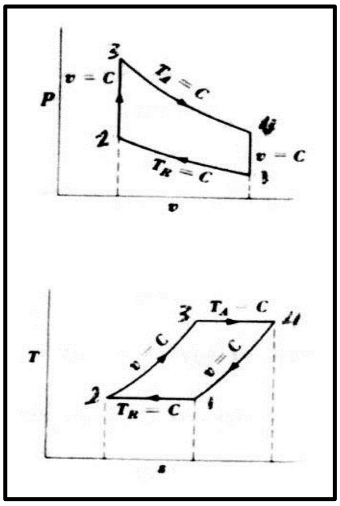
da: constant pressure rejection of heat Q_2.

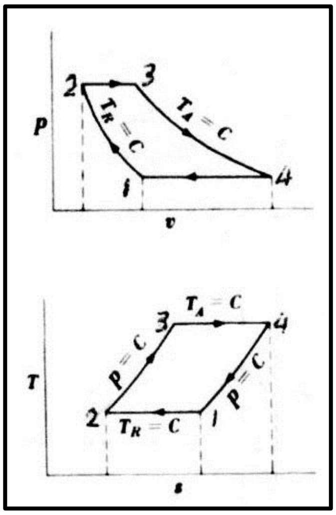
$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{Cp(T_4 - T_1)}{Cp(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \frac{1}{r^{\frac{\gamma-1}{\gamma}}}$$

Regenerative Cycles:

1. Stirling Cycle: It consists of two isothermal; 12 & 34 and two constant volume 2-3 & 41. Heat is added in the constant 2 – 3 and also in the isothermal process 3 – 4. Not that the temperature of initial heat rejection is T_4 is higher than the initial temperature of heat addition T_2, therefore, it is possible to use a heat exchanger to utilize part of the rejected heat to the heat addition process. If the Stirling cycle could be perfectly regenerated, no heat would be necessary for process 23.

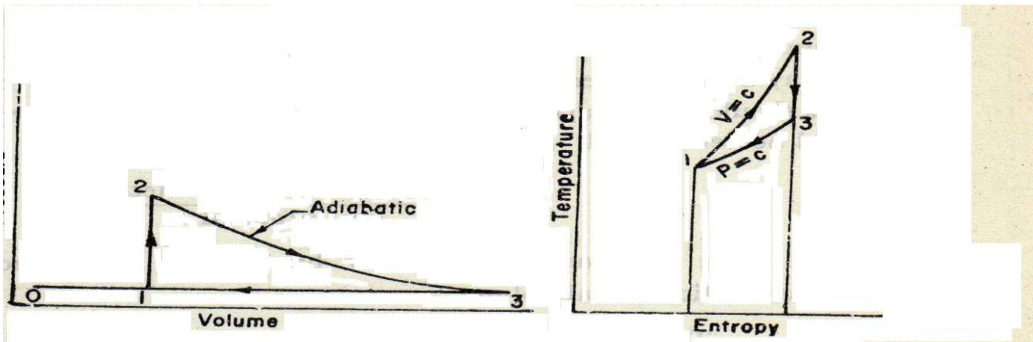




Stirling Cycle Ericsson Cycle

2. Ericsson Cycle: Same comments can be made for Ericsson cycle. Heat is added in the expansion at constant pressure 23 and at constant temperature 34. Heat is rejected in the compression process at constant pressure 41 and at constant temperature 12. Since 23 and 41 are parallel, then gas can be heated from 2 to 3 by cooling from 4 to 1.

Lenoir Cycle:

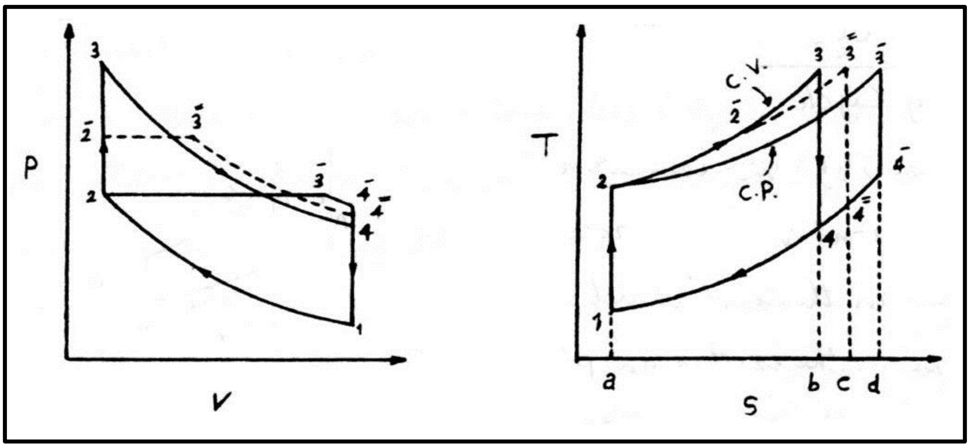


Comparison of Otto, diesel and Dual **Cycles:**

The important parameters in cycle analysis are compression ratio, maximum pressure, maximum temperature, head input, work output, etc.

1. *Equal Compression Ratio and Equal Heat added:*

   The three cycles start from the same point (1); compression process is the same (12) for all cycles, equal heat added means:



$$area\ a23ba = area\ a2\bar{3}da = area\ a2\bar{2}\bar{\bar{3}}ca$$

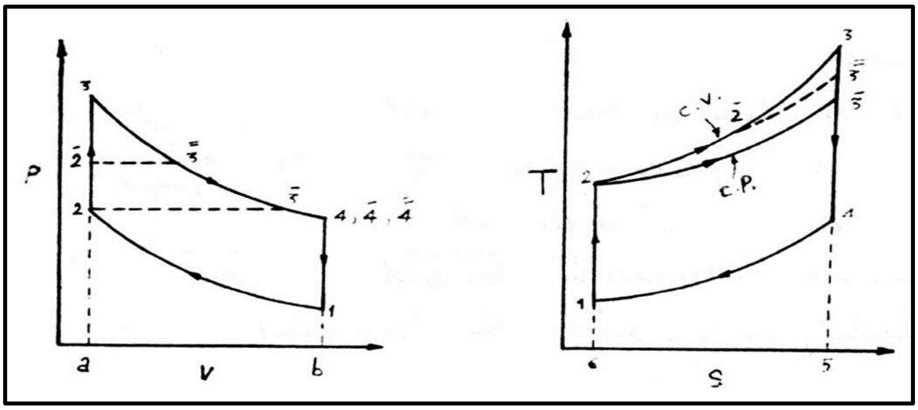
areas representing heat rejected are:

$$area\ a14ba < area\ a1\bar{\bar{4}}ca < area\ a1\bar{4}da$$

$$\eta = \frac{heat\ aded - heat\ rejected}{heat\ added}$$

$$\therefore \eta_{Otto} < \eta_{dual} < \eta_{diesel}$$

2. *Equal Compression Ratio and Heat rejected:*



Processes (12) and (41) are the same in all cycles.
Areas representing heat added are:

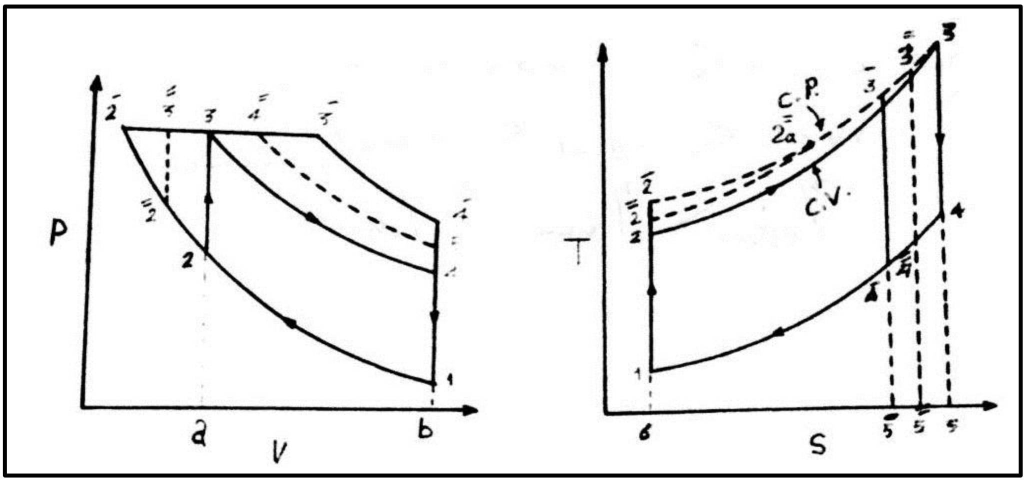
$$area\ 6235 > area\ 62\bar{2}\bar{\bar{3}}5 > area\ 62\bar{3}5$$

Heat rejected area is the same for the three cycles

$$\therefore\ W_{Otto} > W_{dual} > W_{diesel},\ \text{and}$$

$$\eta_{Otto} > \eta_{dual} > \eta_{diesel}$$

3. Equal Maximum Pressure and Equal Heat added:



Point (1) is common in the three cycles.

Maximum pressure is the same, therefore, compression ratio are different as indicated in the diagram above.

Areas representing heat added: $6235 = 6\bar{\bar{2}}\,\bar{\bar{2}}a\,\bar{\bar{3}}5 = 6\bar{2}\bar{3}\bar{5}$

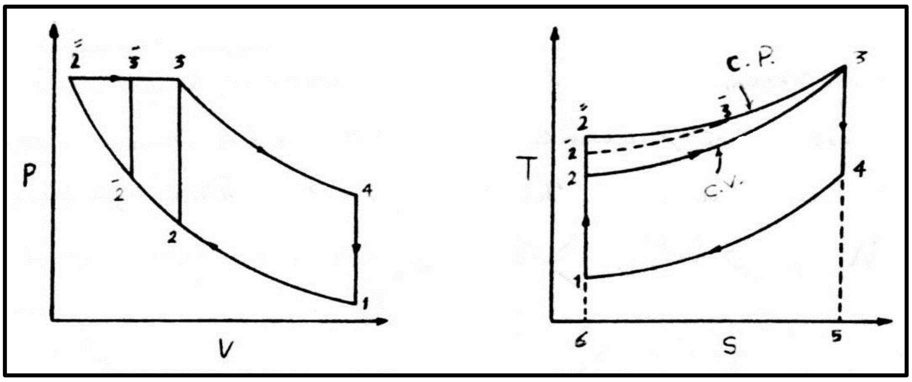
Areas representing heat rejected: $6145 > 61\bar{\bar{4}}\bar{\bar{5}} > 61\bar{4}\bar{5}$

$$\therefore\ W_{Otto} < W_{dual} < W_{diesel}$$

i.e.

$$\eta_{Otto} < \eta_{dual} < \eta_{diesel}$$

4. Equal Maximum Pressure and Maximum Temperature:



Points 1, 3, 4 are common in the three cycles

Heat rejected is the same in the three cycles

Heat added is highest in diesel cycle:

Area $6235 < 6\bar{\bar{2}}335 < 6\bar{\bar{2}}35$

$\therefore W_{Otto} < W_{dual} < W_{diesel}$

i.e

$\eta_{Otto} < \eta_{dual} < \eta_{diesel}$