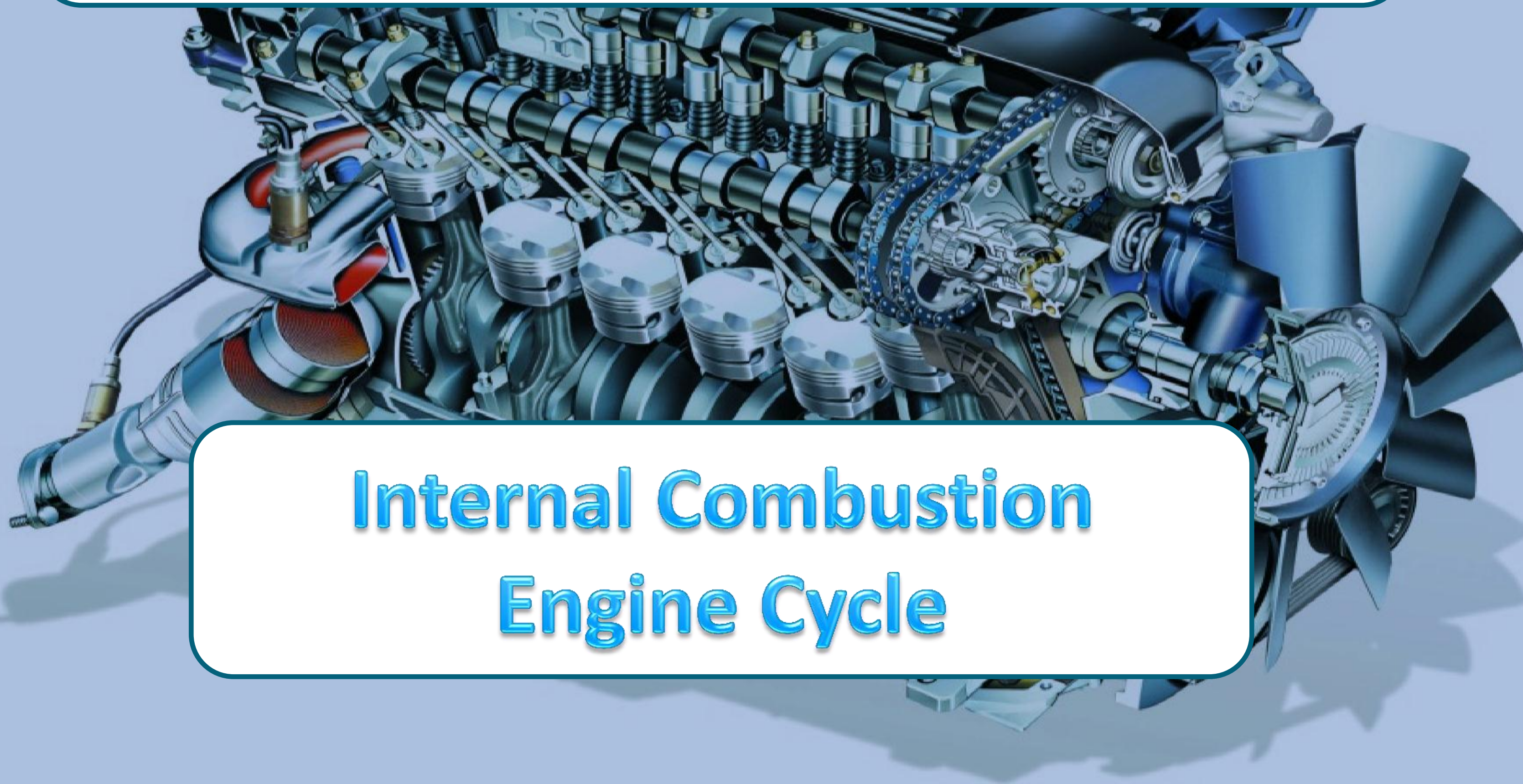
Lecture (4b)
Internal Combustion Engine



Internal Combustion
Engine Cycle

Thermodynamic cycles

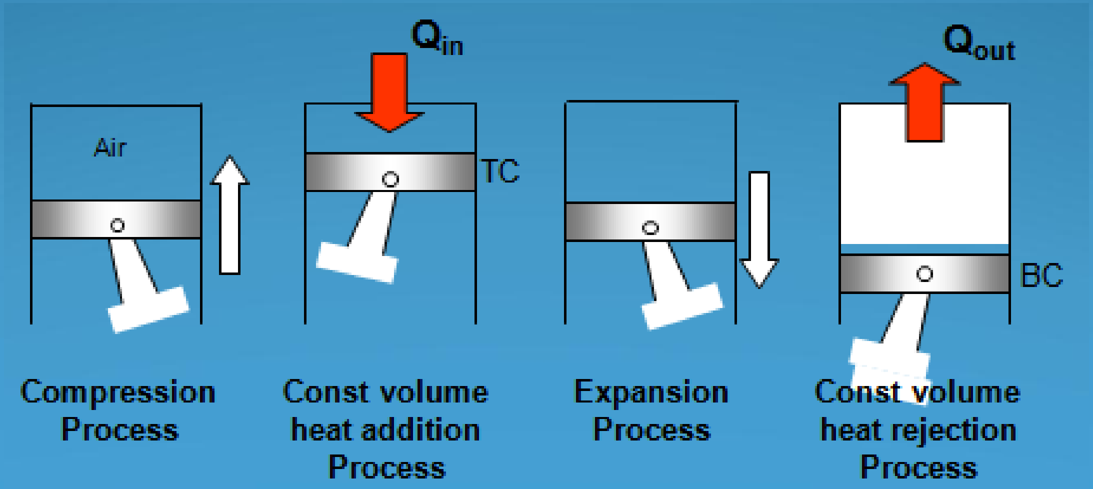
Thermodynamic cycles

- **Engine Cycles**
  - **Air Standard Cycle**
  - **Air - Fuel Cycle**
    - **Theoretical Cycle**
    - **Actual Cycle**

Thermodynamic cycles

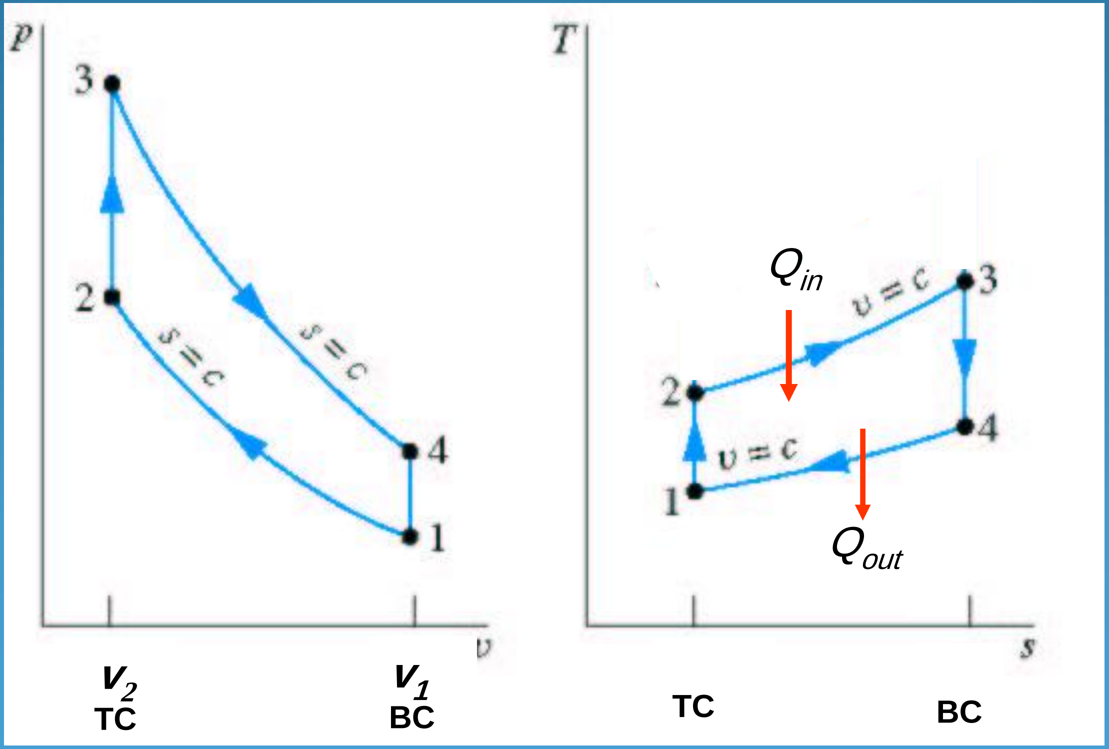
- **Air-standard analysis** is used to perform elementary analyses of IC engine cycles.

- **Simplifications to the real cycle include:**
  1) Fixed amount of air (ideal gas) for working fluid
  2) Combustion process not considered
  3) Intake and exhaust processes not considered
  4) Engine friction and heat losses not considered
  5) Specific heats independent of temperature



Air-Standard Otto cycle

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



Compression ratio:

$$r = \frac{v_1}{v_2} = \frac{v_4}{v_3}$$

Thermodynamic Analysis of Air-Standard Otto Cycle:

Process 1-2 **Isentropic Compression.**

All valves closed.

$$T_2 = T_1 \left(\frac{v_1}{v_2} \right)^{k-1} = T_1 (r_c)^{k-1} \quad \text{and} \quad P_2 = P_1 \left(\frac{v_1}{v_2} \right)^{k} = P_1 (r_c)^{k}$$

$$q_{1-2} = 0$$

$$w_{1-2} = \frac{P_2 v_2 - P_1 v_1}{1-k} = \frac{R(T_2 - T_1)}{1-k} = Cv(T_1 - T_2)$$

Process 2-3 **Constant Volume Heat Input.**

All valves closed.

$$V_3 = v_2 = v_{TDC} \quad \text{so that} \quad \frac{T_3}{T_2} = \frac{P_3}{P_2}$$

$$T_3 = T_{Max.} \quad \text{and} \quad P_3 = P_{Max.}$$

$$q_{2-3} = q_{in} = Cv(T_3 - T_2)$$

$$w_{2-3} = 0$$

Process 3-4 Isentropic Expansion

All valves closed.

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = T_3\left(\frac{1}{r_c}\right)^{k-1} \quad \text{and} \quad P_4 = P_3\left(\frac{v_3}{v_4}\right)^{k} = P_3\left(\frac{1}{r_c}\right)^{k}$$

$$q_{3-4} = 0$$

$$w_{3-4} = \frac{P_4 v_4 - P_3 v_3}{1-k} = \frac{R(T_4 - T_3)}{1-k} = Cv(T_3 - T_4)$$

Process 4-5 Constant Volume Heat Rejection

Exhaust valve open and intake valve closed.

$$v_5 = v_4 = v_1 = v_{BDC} \quad \text{so that} \quad \frac{T_5}{T_4} = \frac{P_5}{P_4}$$

$$q_{4-5} = q_{out} = Cv(T_5 - T_4) = Cv(T_1 - T_4)$$

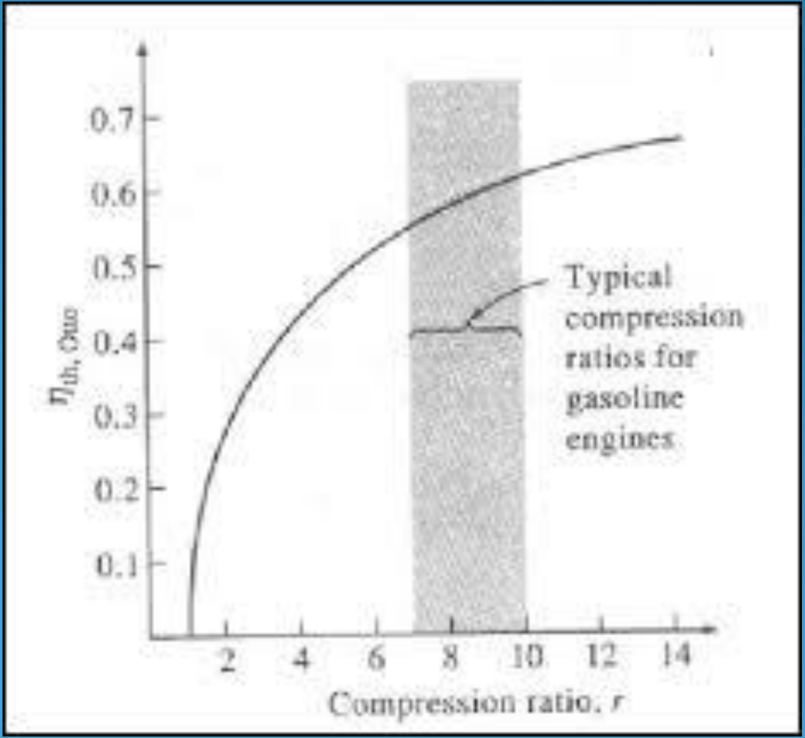
$$w_{4-5} = 0$$

Thermal efficiency of Otto Cycle:

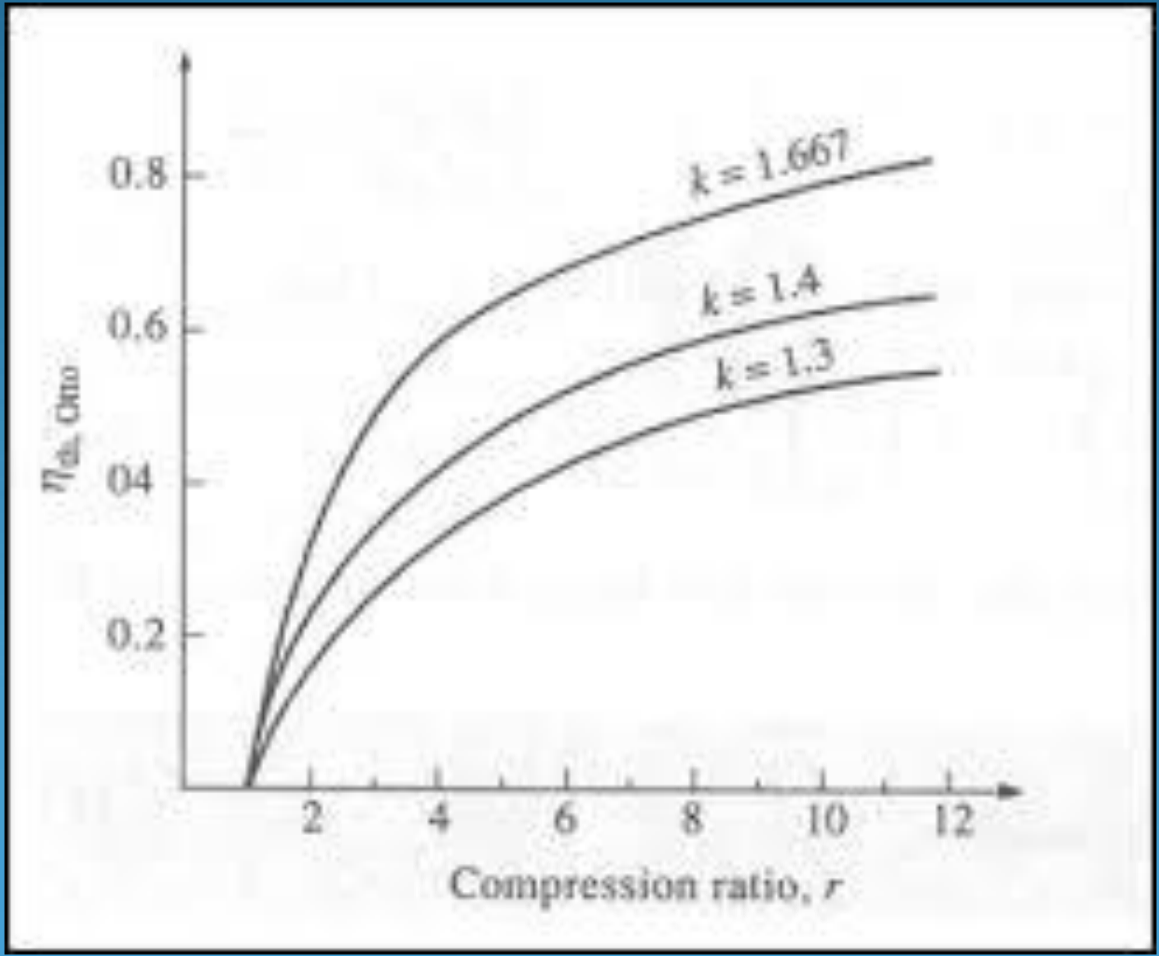
$$\eta_{(Otto)} = \frac{|w_{net}|}{|q_{in}|} = 1 - \frac{|q_{out}|}{|q_{in}|} = 1 - \frac{Cv(T_4 - T_1)}{Cv(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

$$\therefore \eta_{(Otto)} = 1 - \left(\frac{T_1}{T_2}\right) = 1 - \left(\frac{1}{r_c}\right)^{k-1}$$

The effect of compression ratio on thermal efficiency of Otto Cycle:

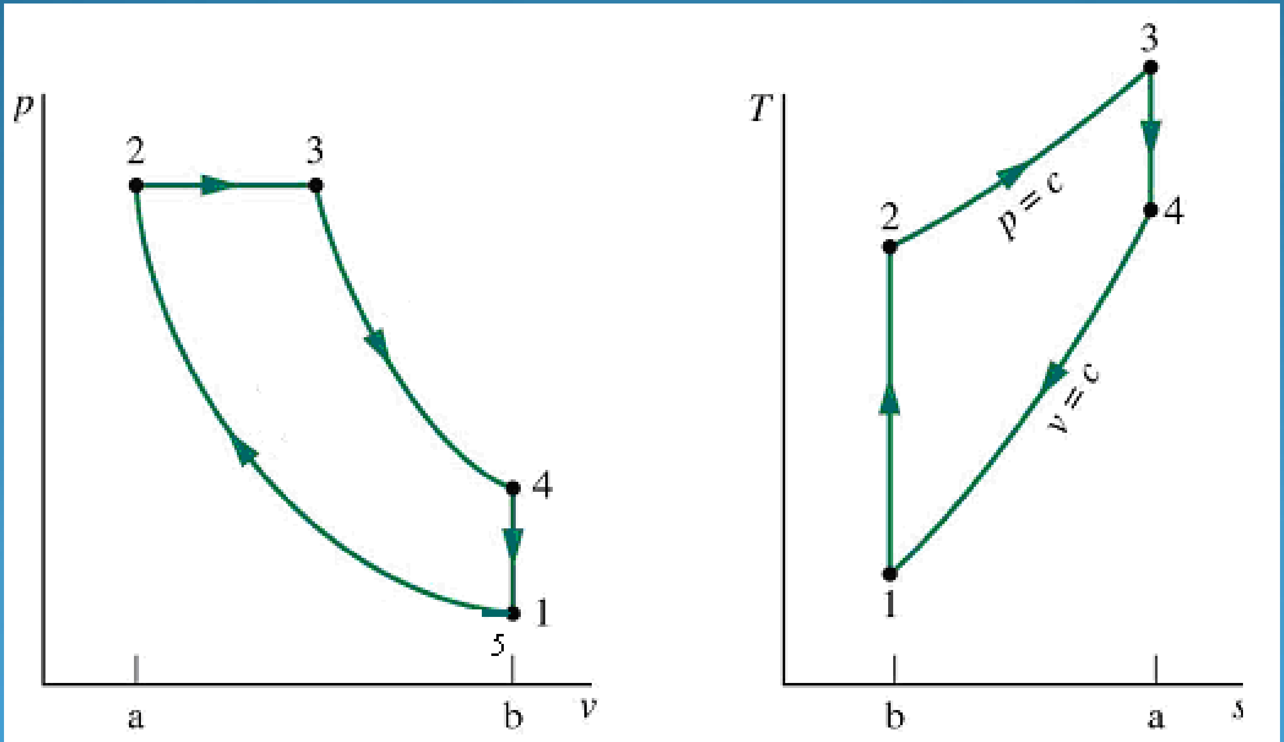


The effect of variation of specific heat constant γ = Cp/Cv on thermal efficiency of Otto Cycle:



Air-Standard Diesel cycle

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



Cut off ratio:

$$\left(r_{cut\ off}\right)=\left(\frac{v_3}{v_2}\right)=\left(\frac{T_3}{T_2}\right)$$

Thermodynamic Analysis of Air-Standard Diesel Cycle:

Process 1-2 **Isentropic Compression Stroke.**

$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = T_1(r_c)^{k-1} \quad \text{and} \quad P_2 = P_1\left(\frac{v_1}{v_2}\right)^{k} = P_1(r_c)^{k}$$

$$q_{1-2} = 0$$

$$w_{1-2} = \frac{P_2 v_2 - P_1 v_1}{1-k} = \frac{R(T_2 - T_1)}{1-k} = Cv(T_1 - T_2)$$

Process 2-3 **Constant Pressure Heat Input. (Combustion)**

$$P_3 = P_2 \quad \text{and} \quad T_3 = T_2\left(\frac{v_3}{v_2}\right) = T_2\left(r_{cut\,off}\right)$$

$$q_{2-3} = q_{in} = Cp(T_3 - T_2)$$

$$w_{2-3} = P_3(v_3 - v_2)$$

Process 3-4 **Isentropic Power or Expansion Stroke.**

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = T_3\left(\frac{r_{cut\,off}}{r_c}\right)^{k-1} \quad \text{and} \quad P_4 = P_3\left(\frac{v_3}{v_4}\right)^{k} = P_3\left(\frac{r_{cut\,off}}{r_c}\right)^{k}$$

$$q_{3-4} = 0$$

$$w_{3-4} = \frac{P_4 v_4 - P_3 v_3}{1-k} = \frac{R(T_4 - T_3)}{1-k} = Cv(T_3 - T_4)$$

Process 4-5 **Constant Volume Heat Rejection. (Exhaust stroke)**

$$v_5 = v_4 = v_1 = v_{BDC} \quad \text{so that} \quad \frac{T_5}{T_4} = \frac{P_5}{P_4}$$

$$q_{4-5} = q_{out} = Cv(T_5 - T_4) = Cv(T_1 - T_4)$$

$$w_{4-5} = 0$$

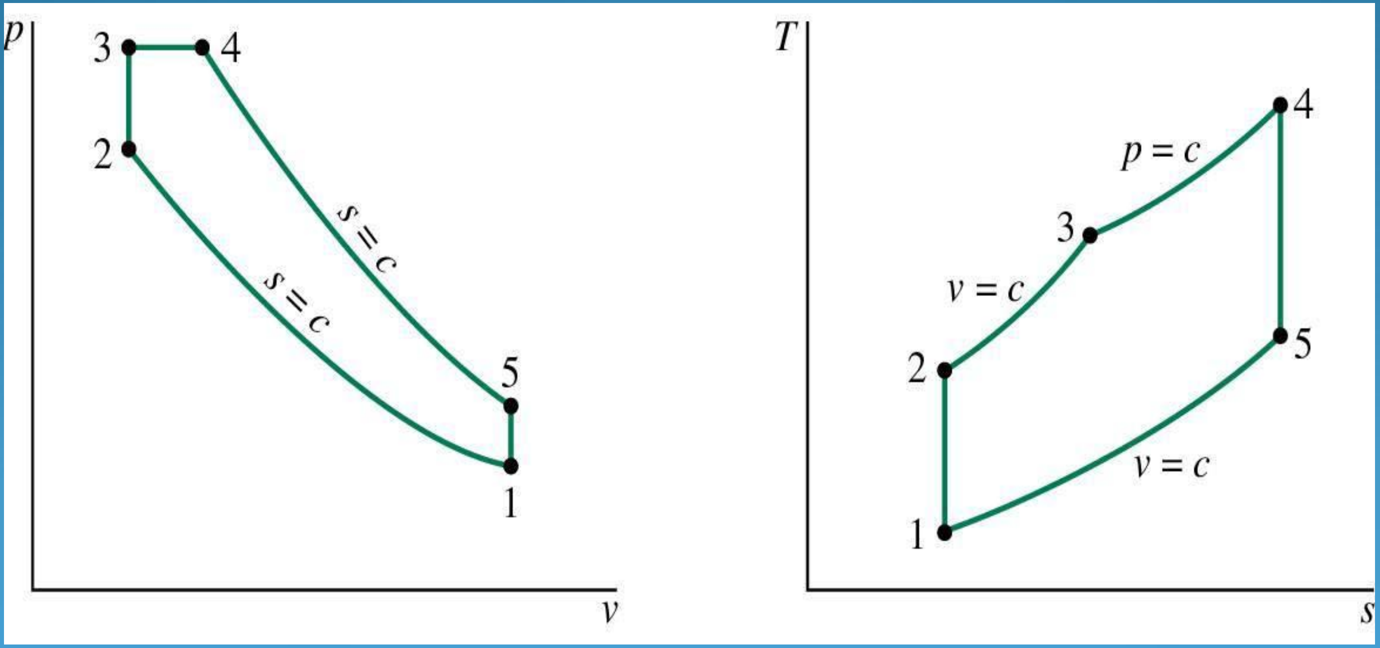
Thermal efficiency of Diesel Cycle:

$$\eta_{(Diesel)} = \frac{|w_{net}|}{|q_{in}|} = 1 - \frac{|q_{out}|}{|q_{in}|} = 1 - \frac{Cv(T_4 - T_1)}{Cp(T_3 - T_2)}$$

$$\therefore \eta_{(Diesel)} = 1 - \left(\frac{1}{r_c}\right)^{k-1} \times \left[\frac{r_{cuttoff}^{k} - 1}{k(r_{cut\,off} - 1)}\right]$$

Air-Standard Dual cycle

Process 1 → 2 Isentropic compression
Process 2 → 3 Constant volume heat addition
Process 3 → 4 Constant pressure heat addition
Process 4 → 5 Isentropic expansion
Process 5 → 1 Constant volume heat rejection



Thermodynamic Analysis of Air-Standard Dual Cycle:

Process 1-2 **Isentropic Compression Stroke.**

$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = T_1(r_c)^{k-1} \quad \text{and} \quad P_2 = P_1\left(\frac{v_1}{v_2}\right)^{k} = P_1(r_c)^{k}$$

$$q_{1-2} = 0$$

$$w_{1-2} = \frac{P_2 v_2 - P_1 v_1}{1-k} = \frac{R(T_2 - T_1)}{1-k} = Cv(T_1 - T_2)$$

Process 2-3 **Constant Volume Heat Input. (Combustion)**

$$V_3 = v_2 = v_{TDC} \quad \text{so that} \quad \frac{T_3}{T_2} = \frac{P_3}{P_2}$$

$$q_{2-3} = q_{in} = Cv(T_3 - T_2)$$

$$w_{2-3} = 0$$

Process 3-4 **Constant Pressure Heat Input. (Combustion)**

$$P_4 = P_3 \qquad \text{and} \qquad T_4 = T_3\left(\frac{v_4}{v_3}\right) = T_3\left(r_{cut\,off}\right)$$

$$q_{3-4} = q_{in} = Cp\left(T_4 - T_3\right)$$

$$w_{3-4} = P_4\left(v_4 - v_3\right)$$

Process 4-5 **Isentropic Power or Expansion Stroke.**

$$T_5 = T_4\left(\frac{v_4}{v_5}\right)^{k-1} = T_3\left(\frac{r_{cut\,off}}{r_c}\right)^{k-1} \qquad \text{and} \qquad P_5 = P_4\left(\frac{v_4}{v_5}\right)^{k} = P_3\left(\frac{r_{cut\,off}}{r_c}\right)^{k}$$

$$q_{4-5} = 0$$

$$w_{4-5} = \frac{P_5 v_5 - P_4 v_4}{1-k} = \frac{R(T_5 - T_4)}{1-k} = Cv\left(T_4 - T_5\right)$$

Process 5-6 **Constant Volume Heat Rejection. (Exhaust stroke)**

$$v_6 = v_5 = v_1 = v_{BDC} \qquad \text{so that} \qquad \frac{T_6}{T_5} = \frac{P_6}{P_5}$$

$$q_{5-6} = q_{out} = Cv(T_6 - T_5) = Cv(T_1 - T_5)$$

$$w_{5-6} = 0$$

Thermal efficiency of Dual cycle:

$$\eta_{(Dual)} = \frac{|w_{net}|}{|q_{in}|} = 1 - \frac{|q_{out}|}{|q_{in}|} = 1 - \frac{Cv(T_5 - T_1)}{Cv(T_3 - T_2) + Cp(T_4 - T_3)}$$

$$\therefore \eta_{(Dual)} = 1 - \left(\frac{1}{r_c}\right)^{k-1} \times \left[\frac{r_p \times r_{cutt\,\mathrm{off}}^{\mathrm{k}} - 1}{k \times r_p (r_{cut\,\mathrm{off}} - 1) + r_p - 1}\right]$$

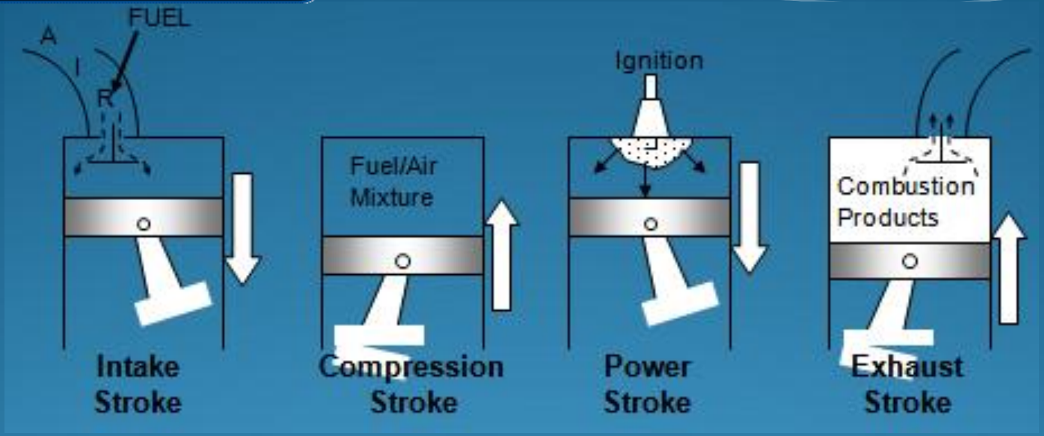
- **Air-fuel cycle**

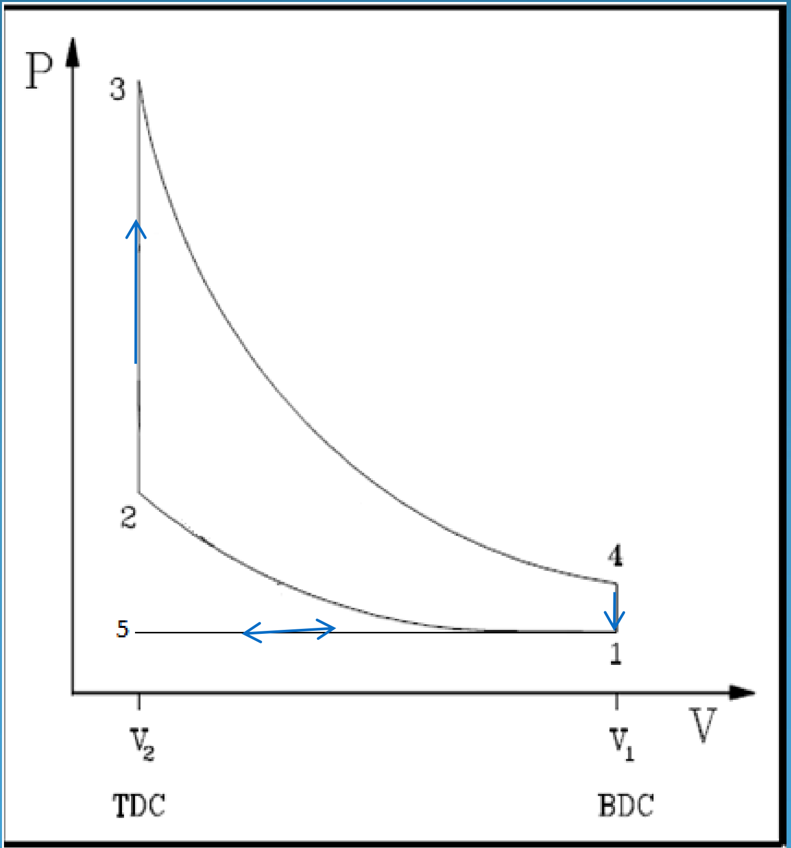
❑ Is the theoretical cycle based on the actual properties of the cylinder contents.

- **Simplifications to the Theoretical Air-Fuel Cycle approximation.**

1- The actual composition of the cylinder contents.
2- The variation in the specific heat of the gases in the cylinder.
3- The dissociation effect.
4- The variation in the number of moles present in the cylinder as the pressure and temperature change.
5- No chemical changes in either fuel or air prior to combustion.
6- Combustion takes place instantaneously at top dead center.
7- All processes are adiabatic.
8- The fuel is mixed well with air.

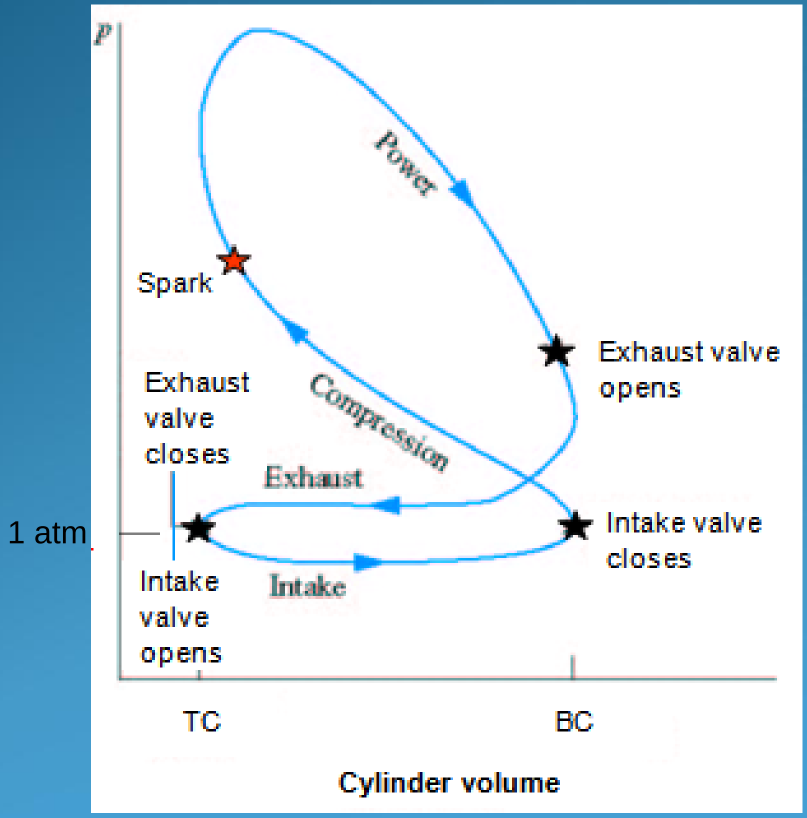
Thermodynamic cycles

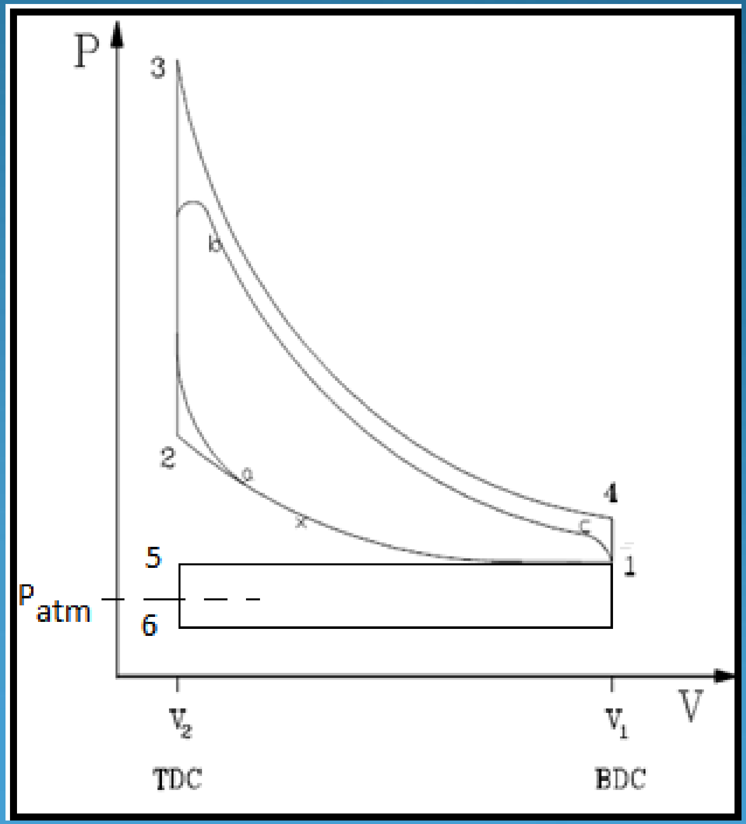




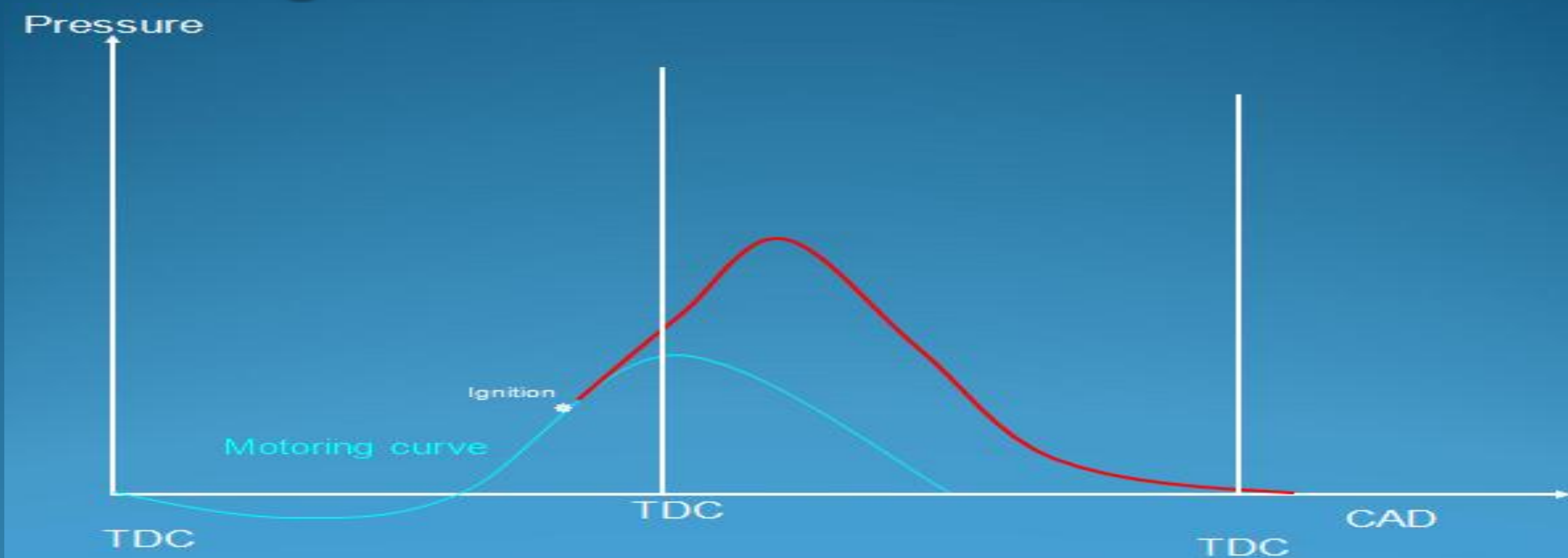
The actual cycle (Otto Cycle)

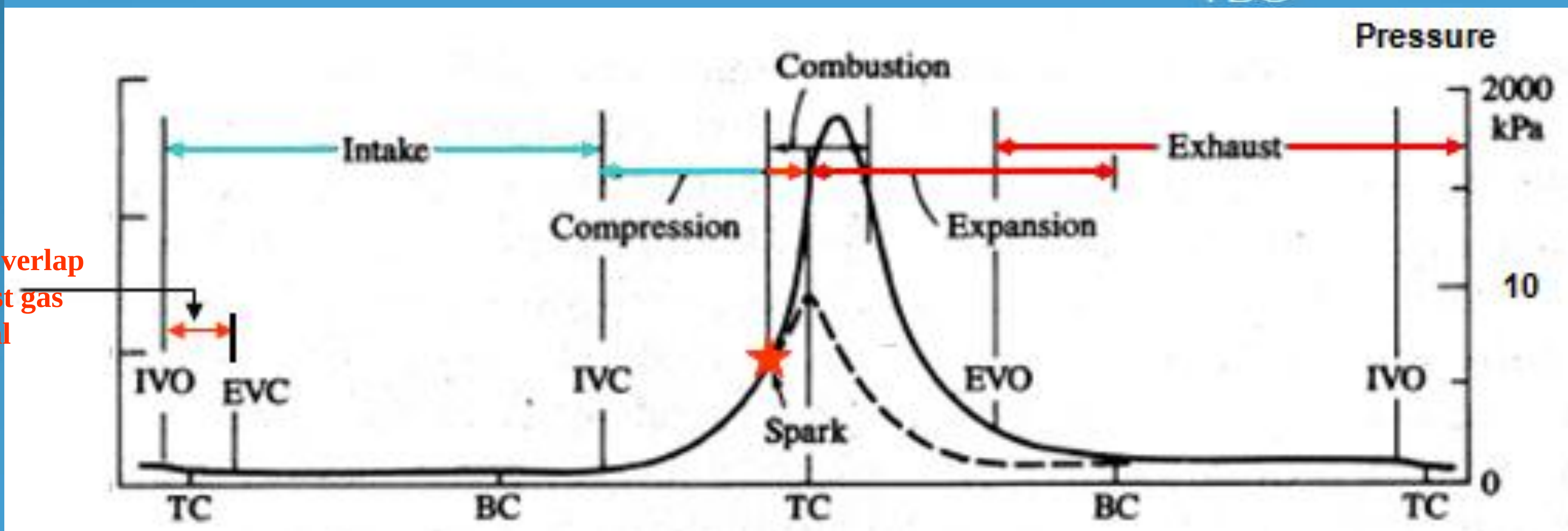
The actual cycle experienced by internal combustion engines is an open cycle with changing composition, actual cycle efficiency is much lower than the air standard efficiency due to various losses occurring in the actual engine.





P- θ Diagram





Valve overlap
Exhaust gas
residual

Differences between Ideal and Actual Cycles

Differences between Ideal and Actual Cycles

1. Leakage :-

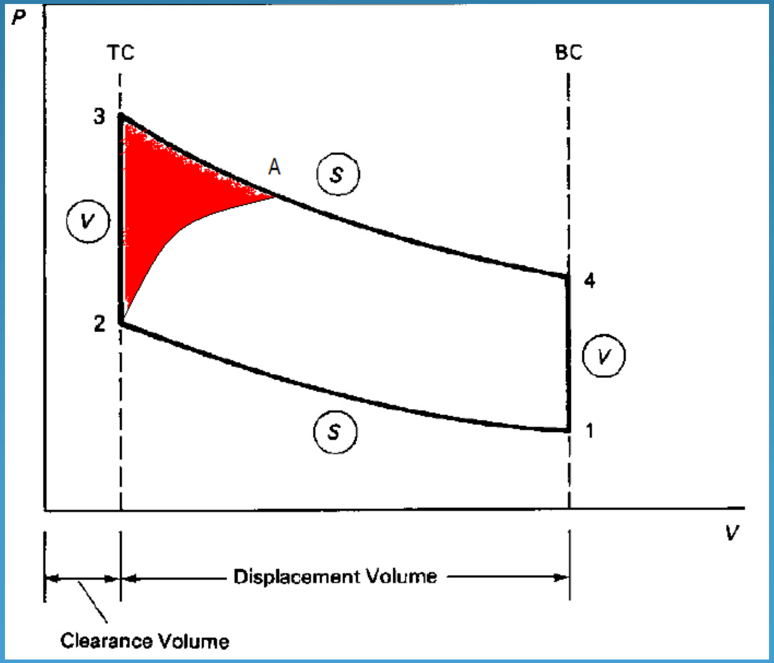
A small amount of combustion pressure can leak past piston rings, Valves or Gasket.

To find this problem make a **Compression Test** by measure the pressure inside the combustion chamber in the compression stroke and compared this with the standard value if P_{test} less than $P_{standard}$ there is leakage.

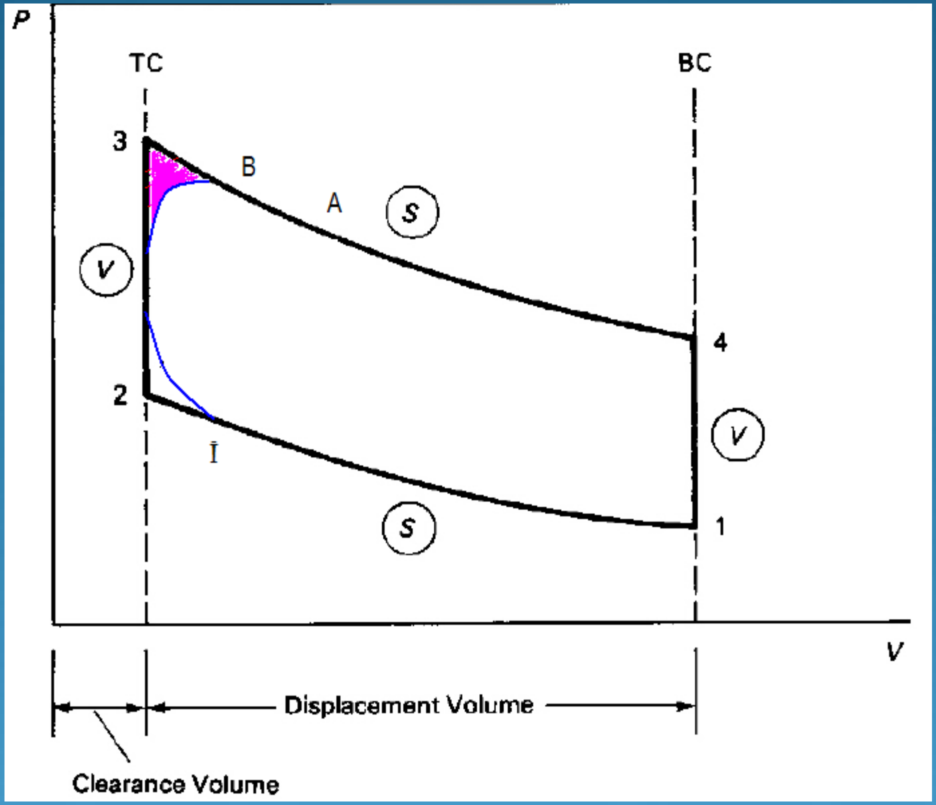
Differences between Ideal and Actual Cycles

2. Time Losses:-

The loss of work due to piston movement during combustion process. Where, combustion does not occur "instantaneously", as a result, there is some piston motion during combustion, so combustion does not occur at constant volume.



Differences between Ideal and Actual Cycles



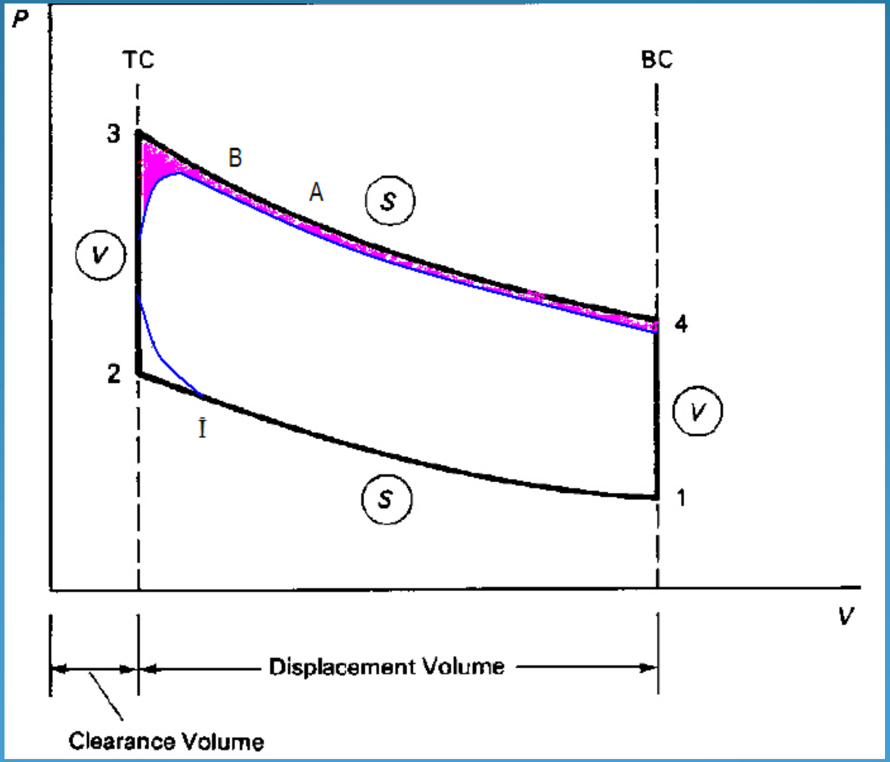
Ignition point: The point at which ignition starts

Spark Advance: “Number of CAD BTD at which Ignition Starts”

Differences between Ideal and Actual Cycles

3. Heat Loss:-

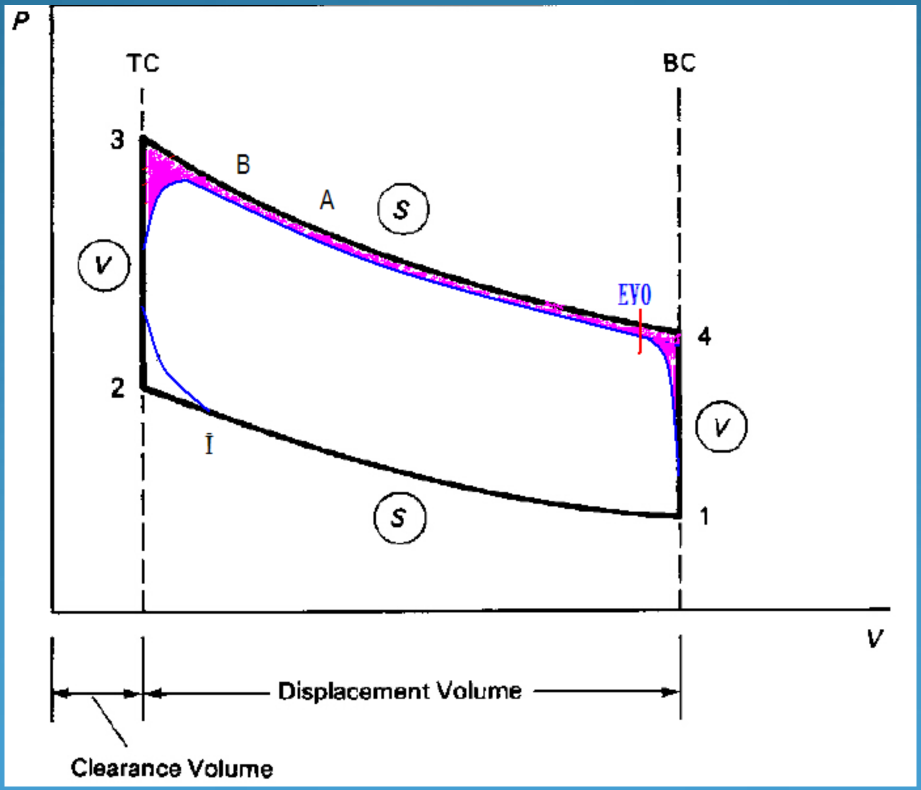
The loss of work due to heat transfer during compression, combustion and expansion strokes



Differences between Ideal and Actual Cycles

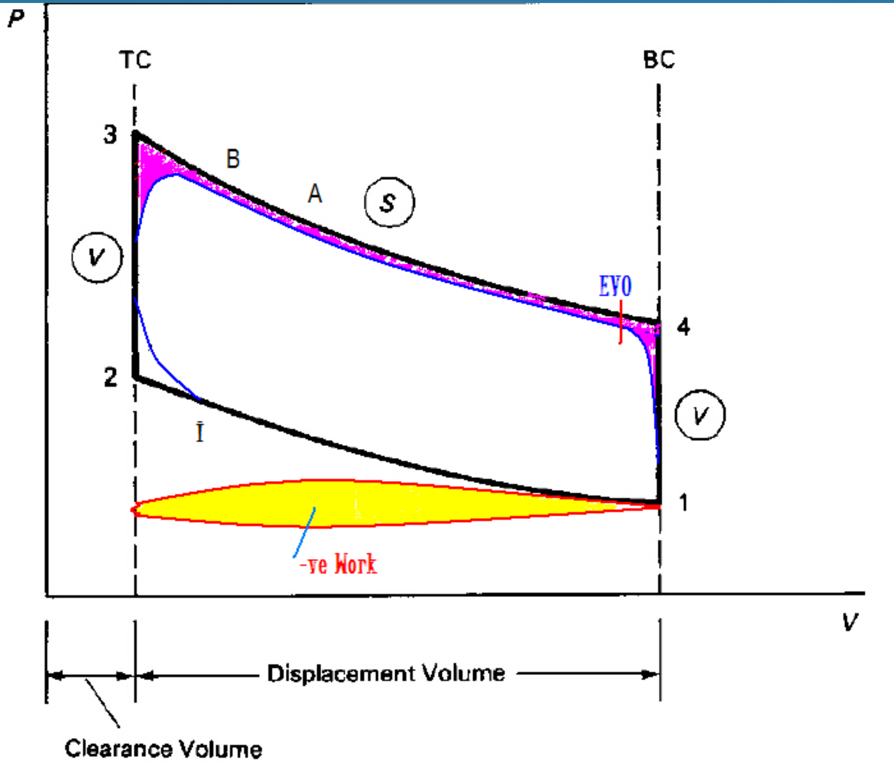
4. Exhaust loss:-

The loss of work due to opening the exhaust valve before B.D.C. by the hot exhaust gasses



5. Pumping work:-

The work required to pump the charge inside the cylinder and exhaust gases outside the cylinder.

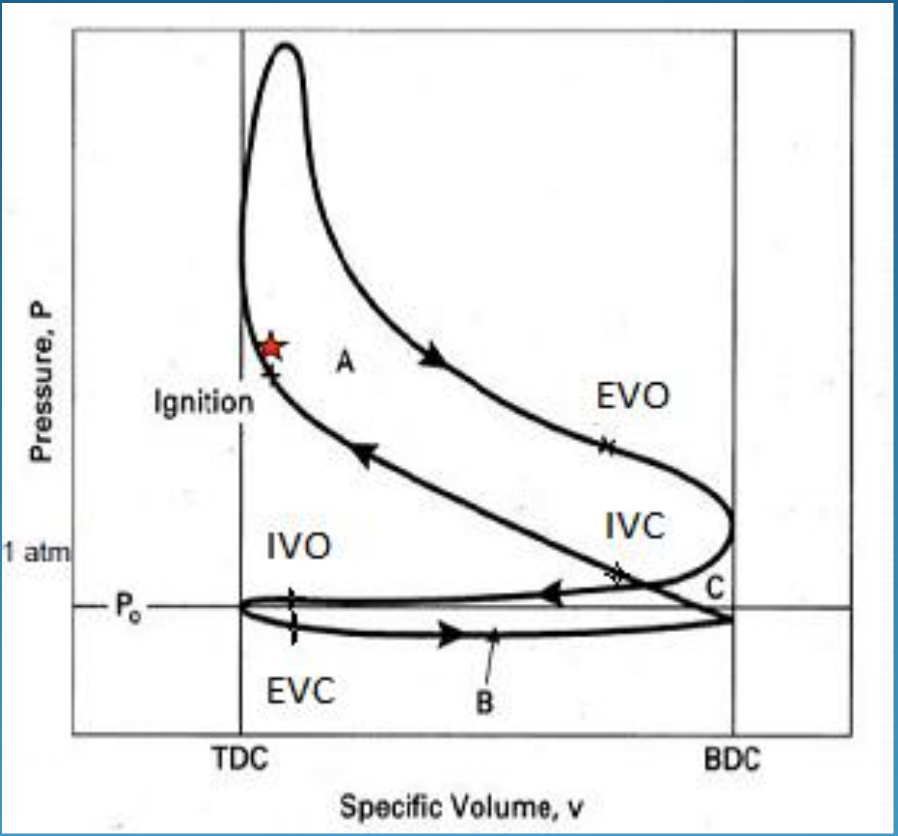


Differences between Ideal and Actual Cycles

6. Progressive Burning :-

Combustion usually starts at a single point, and proceeds with a moving "flame front". Combustion time varies with fuel composition (which affects flame speed), combustion chamber size and shape, location and number of ignition sources, engine speed, and other engine operating conditions.

Differences between Ideal and Actual Cycles



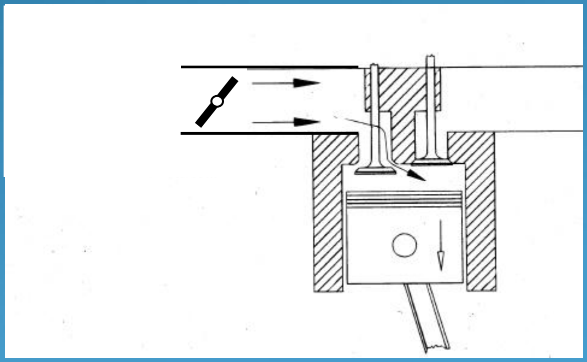
Actual cycle efficiency < Air standard cycle efficiency

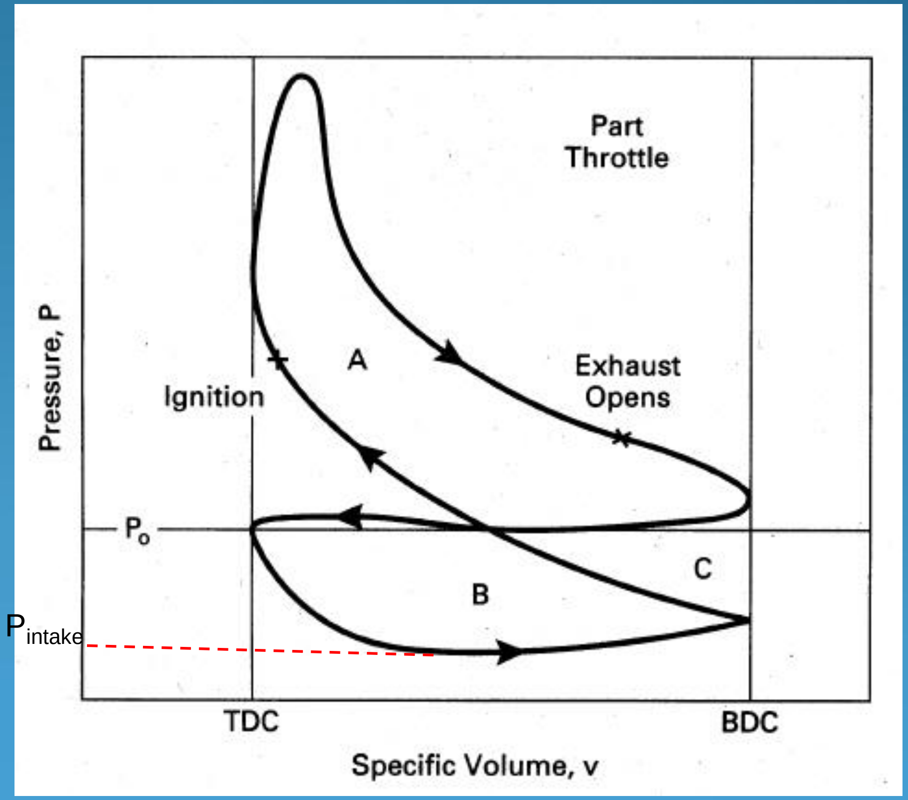
$$\eta_r = \frac{\eta_{act}}{\eta_{airst}}$$

Actual Intake and Exhaust Strokes

Throttled stroke

The pressure at the intake port is significantly lower than atmospheric pressure





Valve Timing

Definitions:-

Valve timing:-
No. of crank angles during which the valve is open.

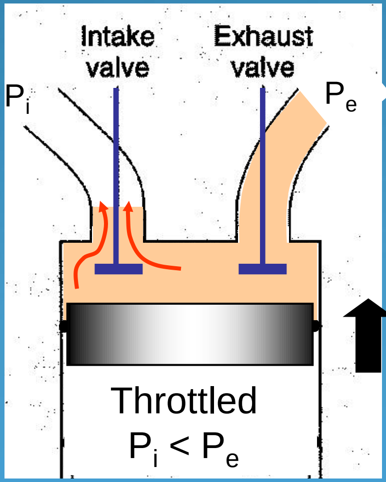
Valve overlap:-
No. of crank angles during which the two valves are open at the same time

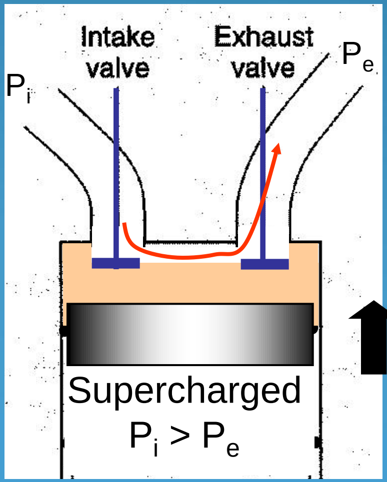
Valve overlap

When the intake valve opens BTDC the cylinder pressure is at roughly P_e

Part throttle ($P_i < P_e$): residual gas flows into the intake port. During intake stroke the residual gas is first returned to the cylinder then fresh gas is introduced. Residual gas reduces part load performance.

Supercharged ($P_i > P_e$): fresh gas can flow out the exhaust valve





Valve Timing

		Open	Close	Duration
Intake	Conventional	5° before tdc	45° after bdc	230°
	High performance	30° before tdc	75° after bdc	285°
Exhaust	Conventional	45° before bdc	10° after tdc	235°
	High performance	70° before bdc	35° after tdc	285°

Overlap

15°

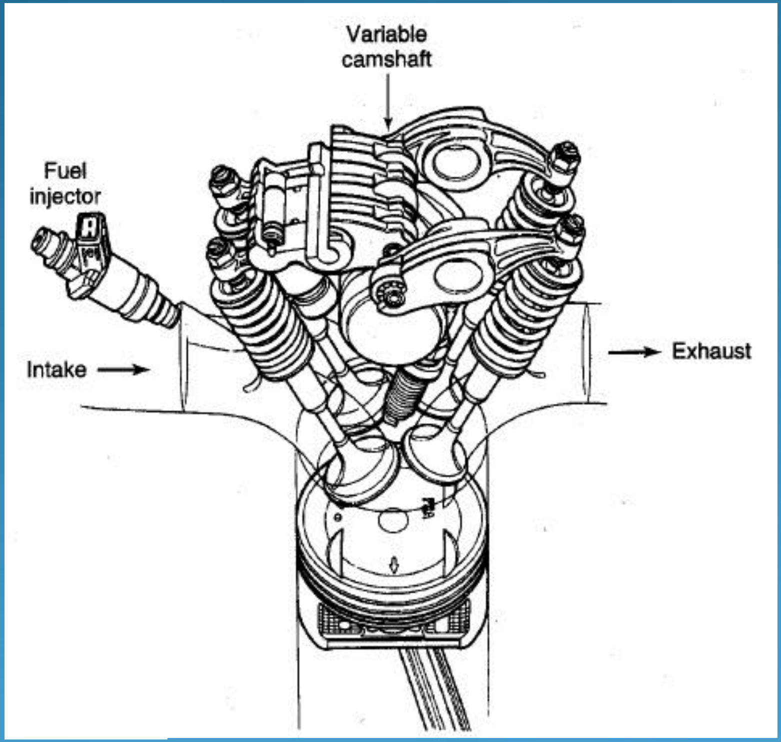
65°

At high engine speeds less time available for fresh gas intake so need more crank angles to get high volumetric efficiency → large valve overlap

At low engine speed and part throttle valve overlap is minimized by reducing the number of CA the intake valve stays open.

Valve Timing

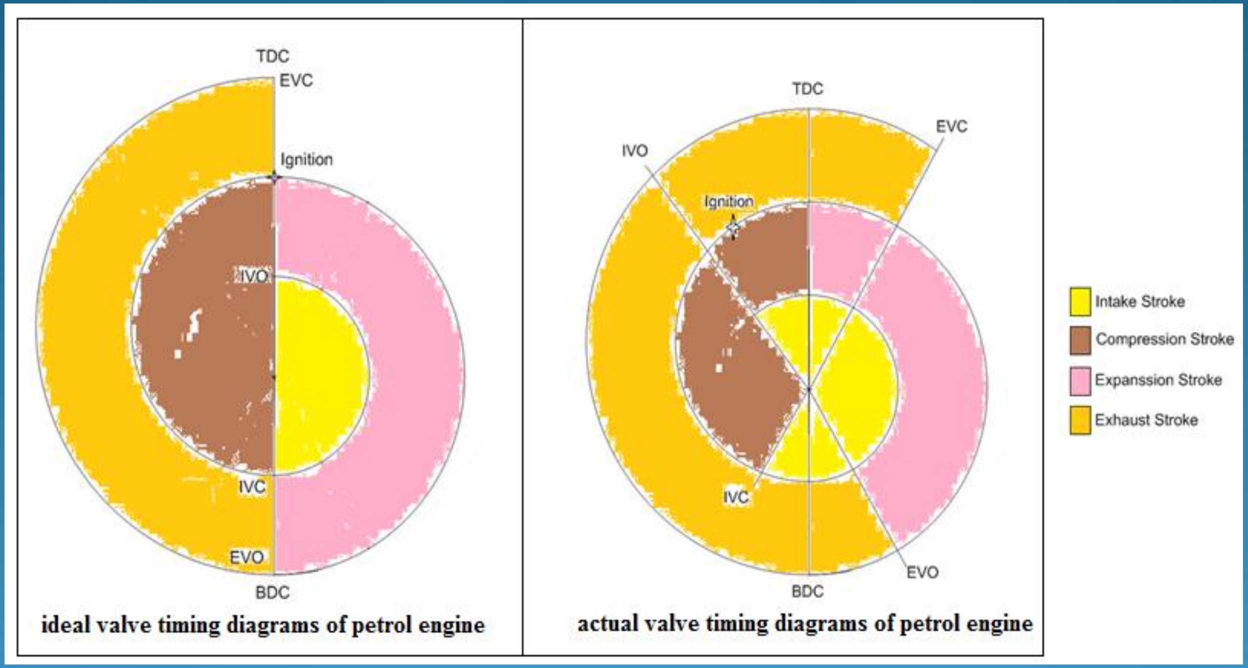
Honda Variable valve Timing and lift Electronic Control (VTEC)



Solenoid Activated Valves

Valve Timing

- The difference between ideal and actual valve timing diagrams of petrol engine



For ideal valve time:

The intake valve open at TDC and closed at BDC.

The exhaust valve open at BDC and closed at TDC.

For actual valve time:

The intake valve open (10^o) before TDC and closed (50^o:70^o)after BDC.

The exhaust valve open (40^o:50^o) before BDC and closed (15^o:30^o) after TDC.

This difference to overcome the mechanical motion of the valve.